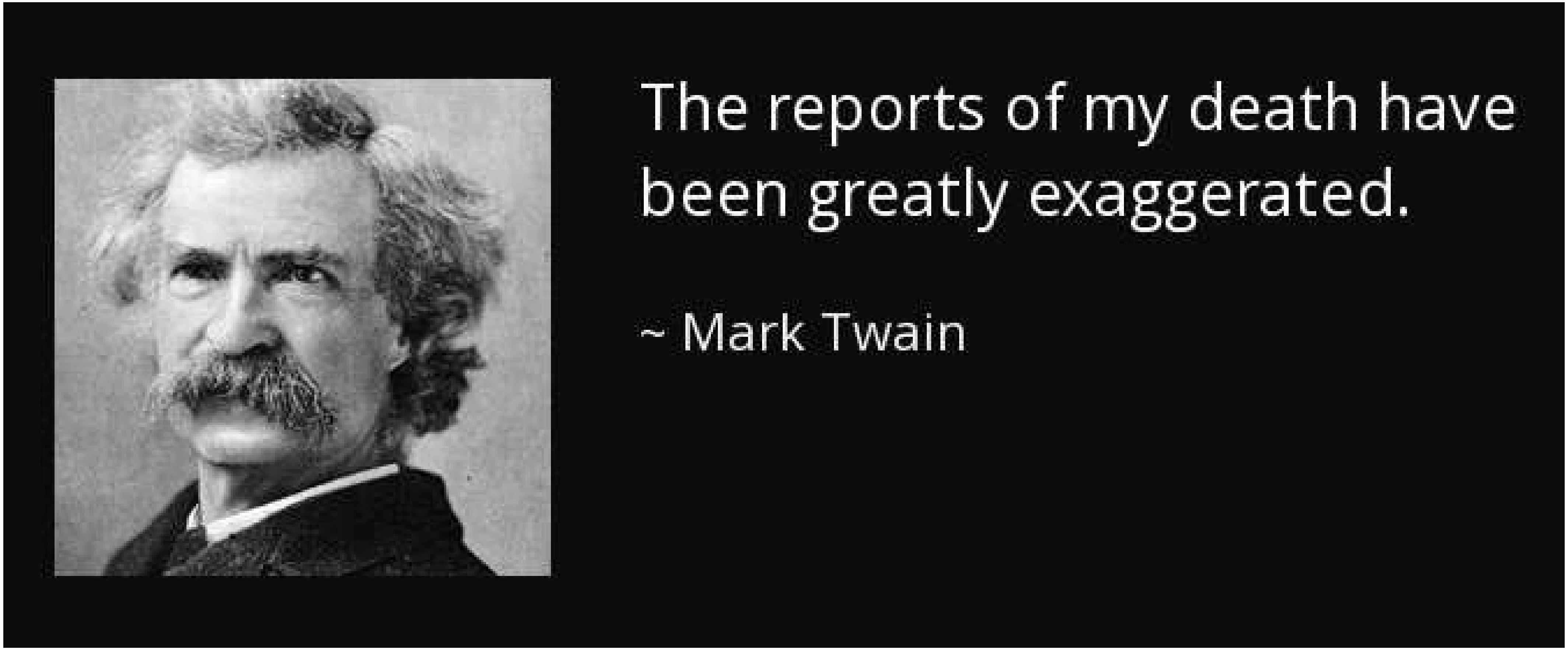
Some original SUSY literature:



Where We Will Discover SUSY

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Singapore, 03/2018

- Motivation & Models
- Results and predictions in GUT based models
- Results and predictions in the pMSSM11
- $\phi_{96} \to \gamma\gamma$
- Conclusions

1. Motivation & Models

Fact:

$\boxed{\text{The SM cannot be the ultimate theory!}}$

1. gravity is not included
2. the hierarchy problem
3. Dark Matter is not included
4. neutrino masses are not included
5. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

$\Rightarrow$ Time to get ready for BSM physics

Which model should we focus on?

Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

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Simple SUSY models predicted correctly:

– top quark mass
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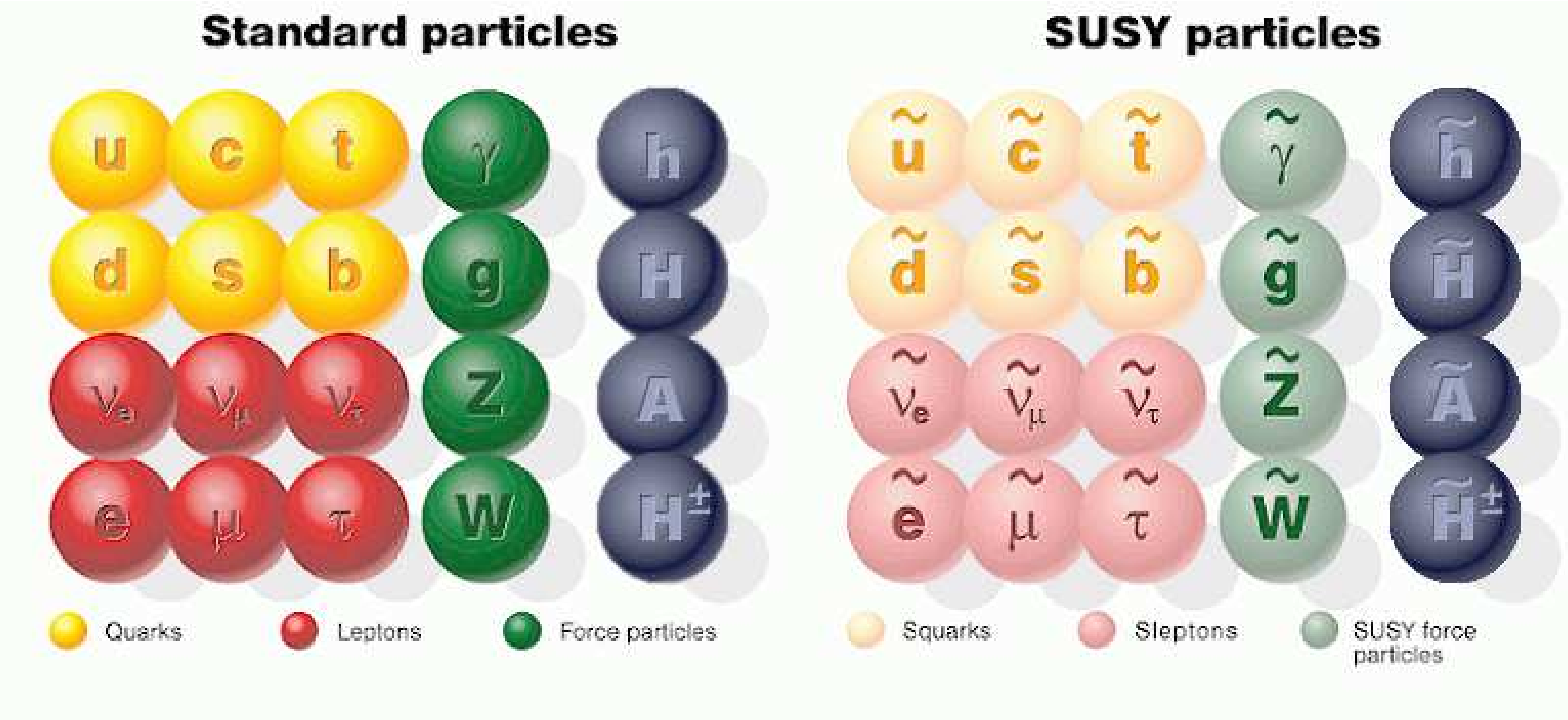
$\Rightarrow$ good motivation to look at SUSY! :-)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} V &= m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ &\quad + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2 \end{aligned}$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

most general case:

$\Rightarrow$ 105 new parameters: masses, mixing angles, phases

$\Rightarrow$ no model missed (within the MSSM)

$\Rightarrow$ $\mathcal{O}(100)$ parameters difficult to handle

B. Constrained models:

CMSSM, NUHM1, NUHM2, SU(5), mAMSB, . . . :

assumption on the scenario that achieves spontaneous SUSY breaking

$\Rightarrow$ prediction for soft SUSY-breaking terms
in terms of small set of parameters

$\Rightarrow$ easy to handle

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

$$\left.\begin{array}{l} m_0 : \text{universal scalar mass parameter} \\ m_{1/2} : \text{universal gaugino mass parameter} \\ A_0 : \text{universal trilinear coupling} \end{array}\right\} \text{at the GUT scale}$$

$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

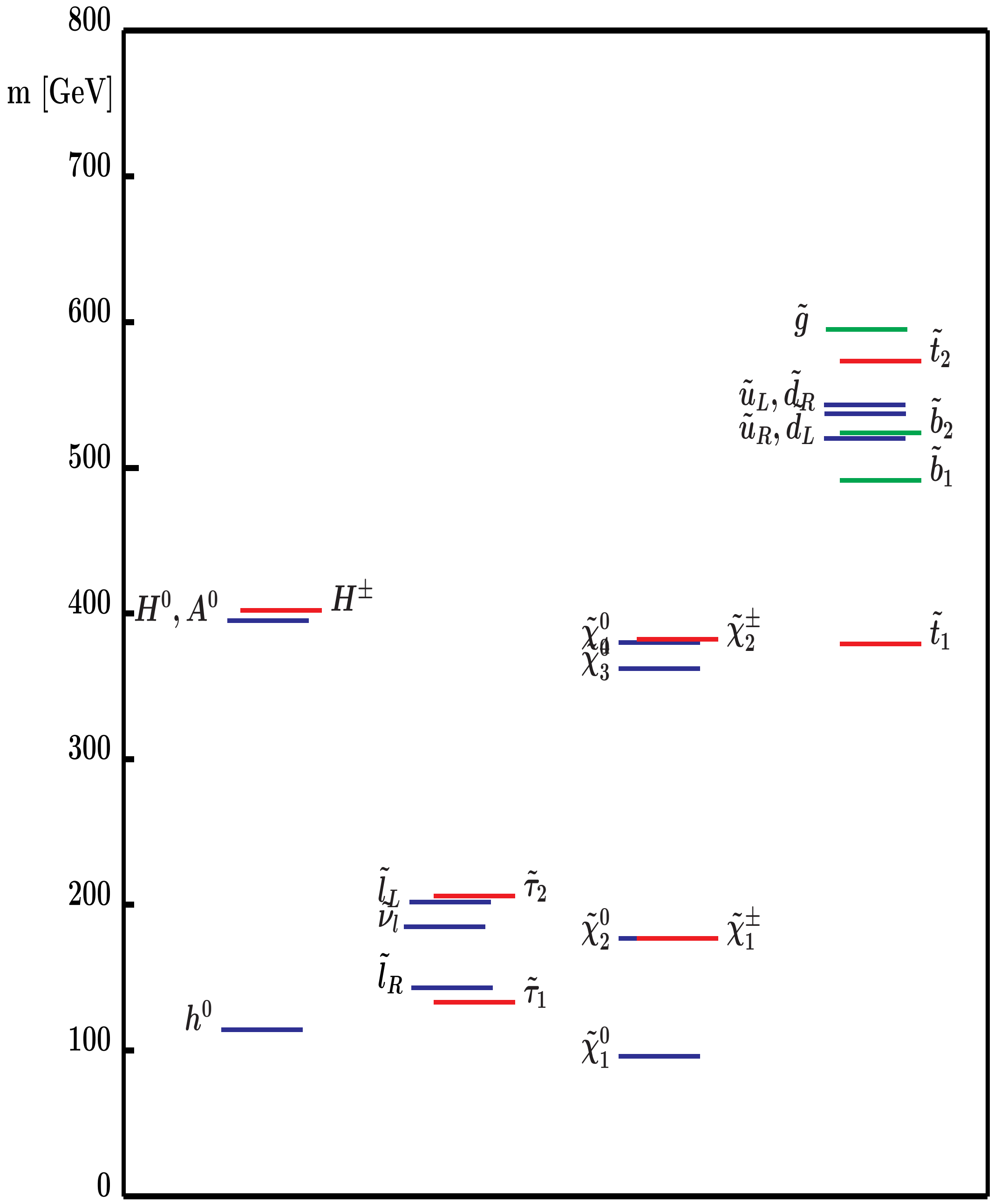
⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ DM!

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

Close connection between

all the sectors



GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A as free parameters at the EW scale

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu \text{ and } M_A$$

GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A and μ as free parameters at the EW scale

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \text{ and } M_A$$

GUT based models: 4.) SU(5) GUT:

Assumption I:

no unification of scalar Higgs parameter at the GUT scale

($\Rightarrow$ effectively M_A and μ as free parameters at the EW scale)

Assumption II:

$$(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i, \;\; (\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$$

$\Rightarrow$ Scenario characterized by

$$m_5, \; m_{10}, \; m_{1/2}, \; A_0, \; \tan\beta, \; m_{H_u}, \; m_{H_d}$$

GUT based models: 5.) mAMSB:

mAMSB scenario characterized by

$$m_{3/2}, m_0, \tan\beta, \mathrm{sign}(\mu)$$

$m_{3/2} = \langle F \rangle / M_{\text{Planck}}$: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term
introduced in order to keep squares of slepton masses positive

typical feature: very small neutralino–chargino mass difference
$\Rightarrow \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \pi^\pm$ with very soft pions

Problem: We cannot be sure about the SUSY-breaking mechanism

⇒ it is possible that with the CMSSM, NUHM1, NUHM2, SU(5), mAMSB
we missed the “correct” mechanism

⇒ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches

Problem: We cannot be sure about the SUSY-breaking mechanism

$\Rightarrow$ it is possible that with the CMSSM, NUHM1, NUHM2, SU(5), mAMSB we missed the "correct" mechanism

$\Rightarrow$ hint: strong connection between colored and uncolored sector tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the "general MSSM"

$\Rightarrow$ 11 parameters are manageable $\Rightarrow$ pMSSM11

- squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$, $m_{\tilde{q}_3}$
- slepton mass parameter(s): $m_{\tilde{l}}$, $m_{\tilde{\tau}}$
- gaugino masses: M_1, M_2, M_3
- trilinear coupling: A
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing paramter: μ

Our tool: **MasterCode**

⇒ collaborative effort of theorists and experimentalists
[Bagnaschi, Borsato, Buchmüller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Liu, Lucio, Martinez Santos, Olive, Richards, Sakurai, Weiglein]

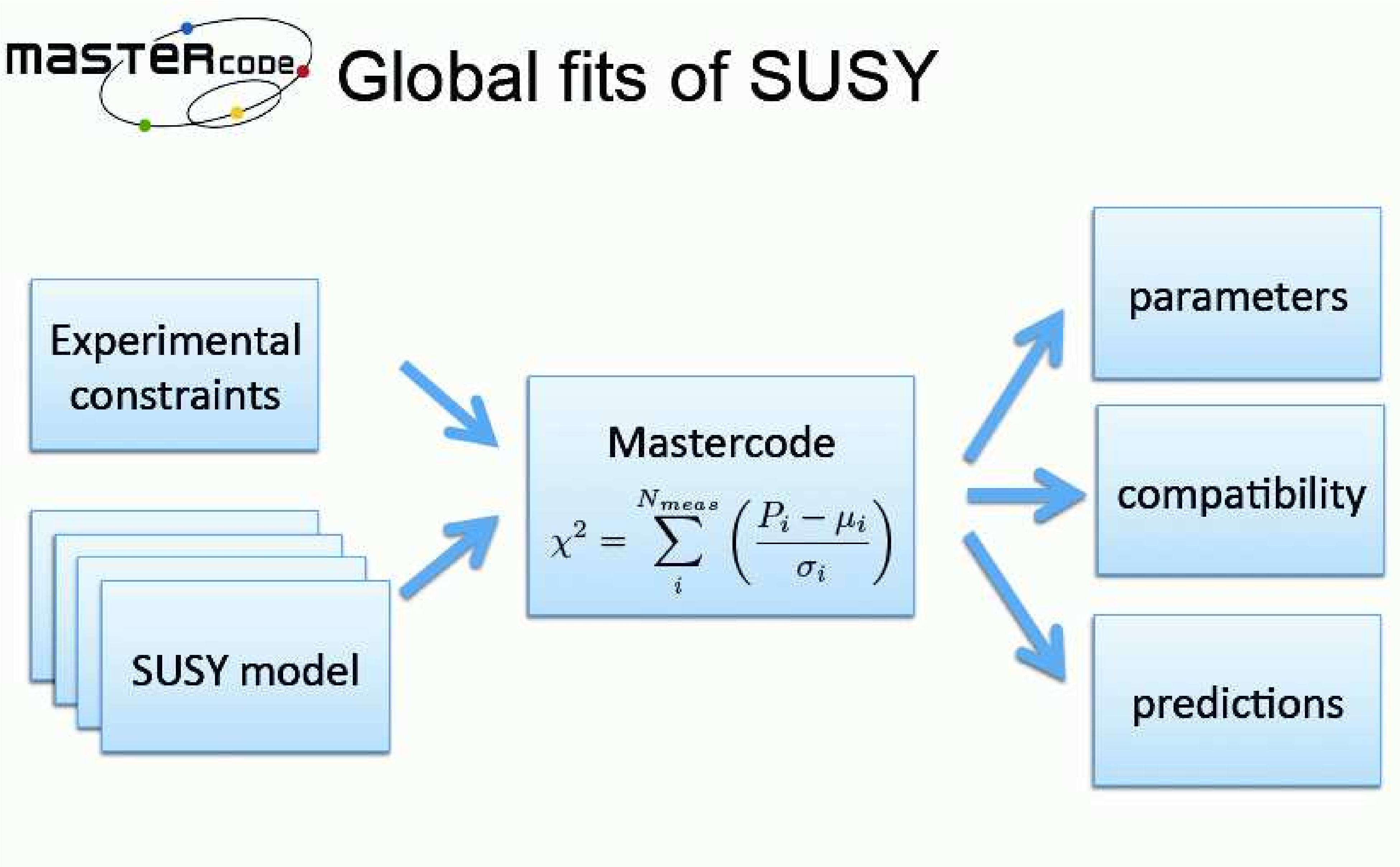
Über-code for the combination of different tools:

– Über-code original in Fortran, now re-written in C++
– tools are included as subroutines
– compatibility ensured by collaboration of
authors of "MasterCode" and authors of "sub tools" /SLHA(2)
– sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently
with various tools

cern.ch/mastercode

The χ^2 evaluation:



Data we have:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

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- SUSY searches (LHC) $\Rightarrow$ own re-cast (Fastlim approach)

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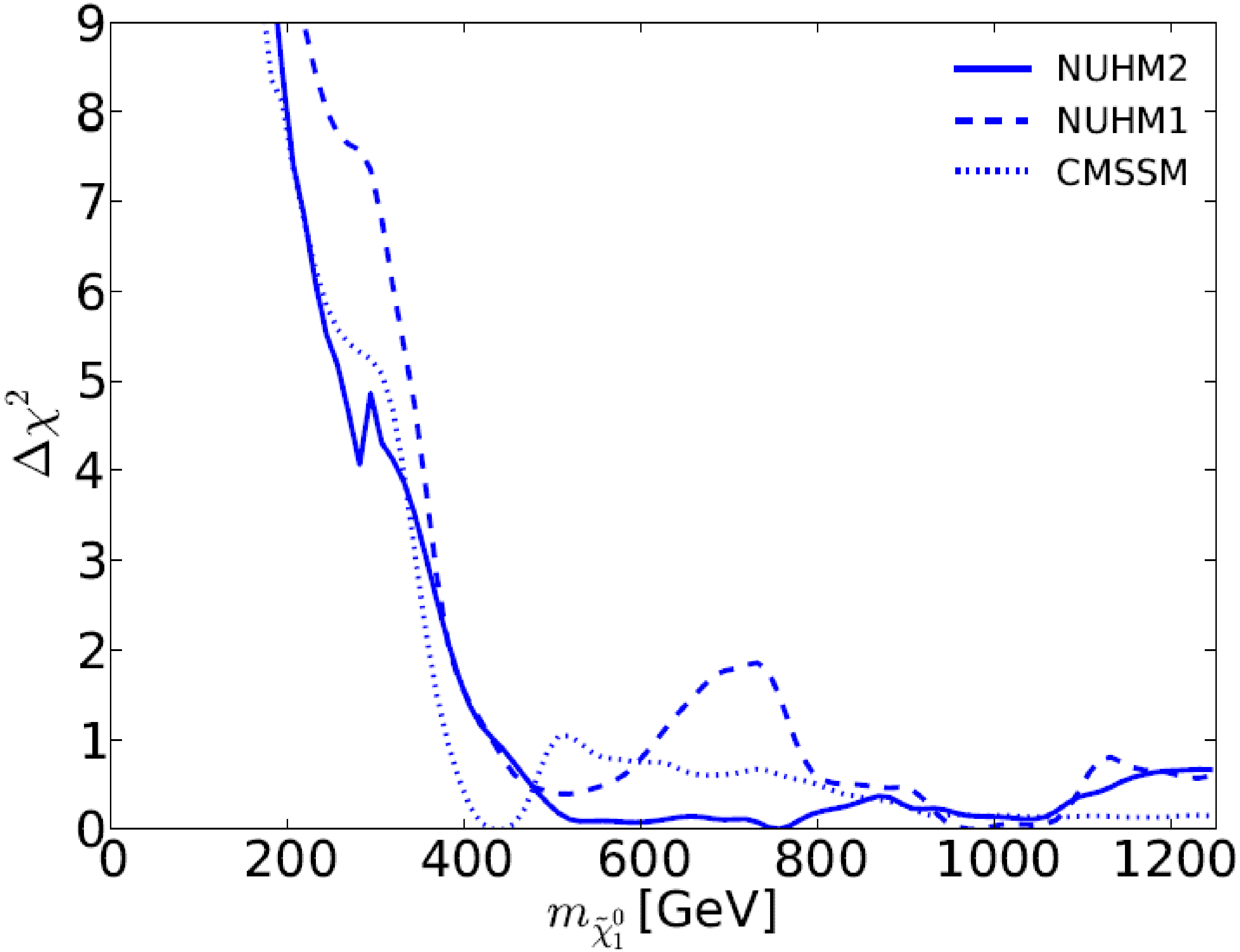
- SUSY searches (LHC) $\Rightarrow$ own re-cast (Fastlim approach)

- electroweak precision data $\Rightarrow$ FeynWZ, FeynHiggs
- flavor data $\Rightarrow$ SuperIso, SuFla
- astrophysical data (DM properties) $\Rightarrow$ MicrOMEGAs, SSARD

2. Results and predictions in GUT based models

[2014]

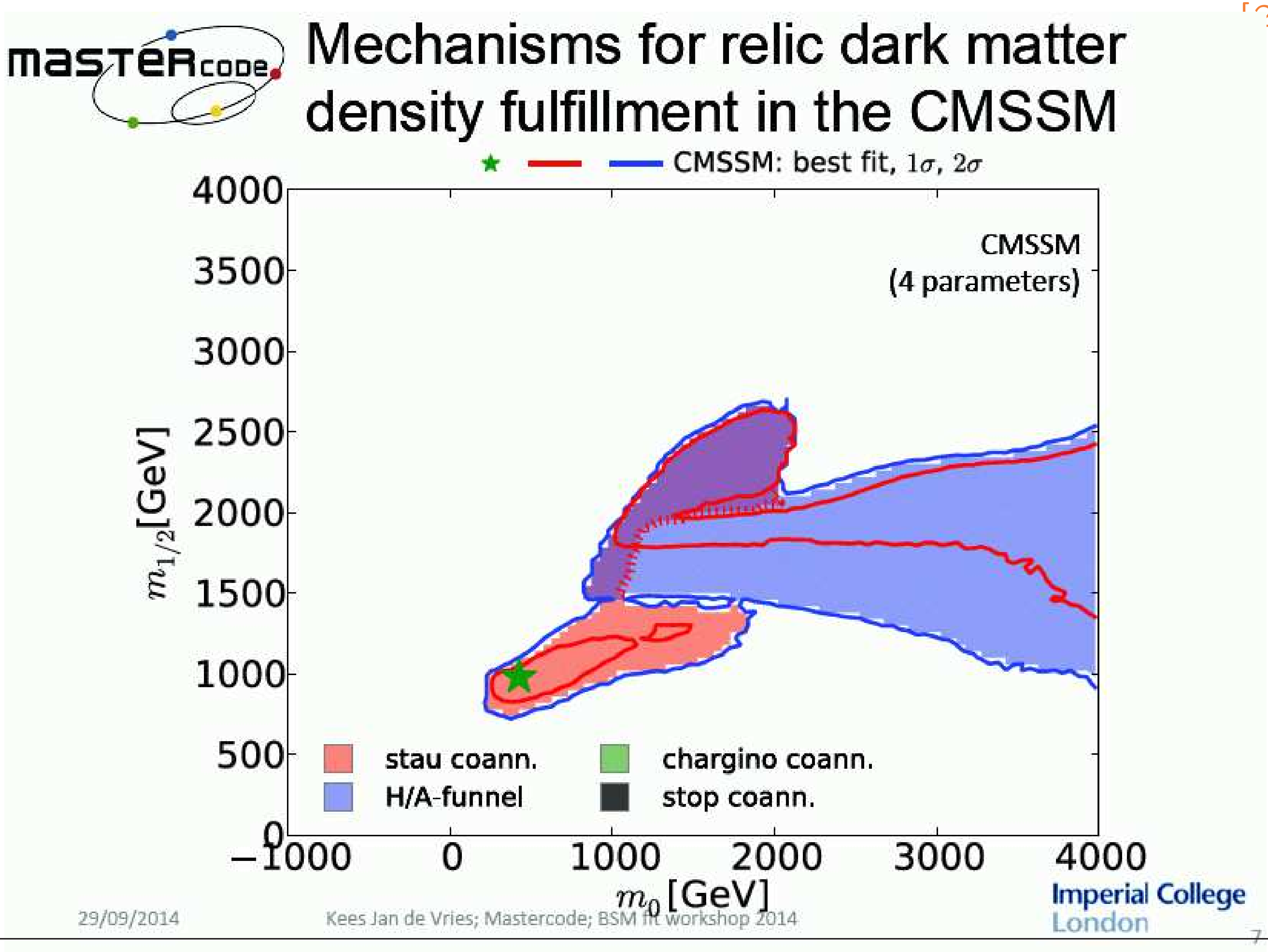
Results in the CMSSM, NUHM1, NUHM2



$\Rightarrow$ only very large values are favored

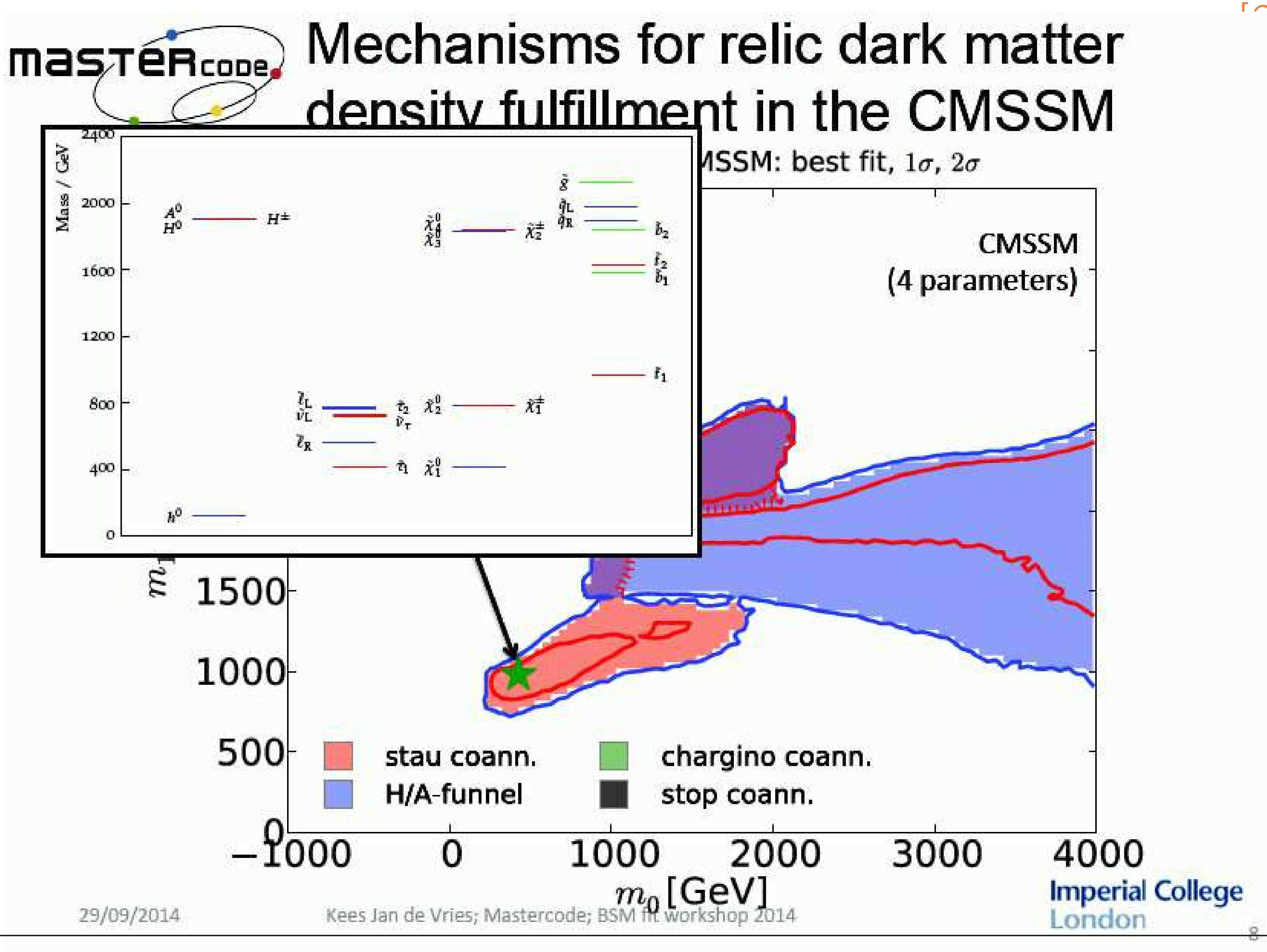
CMSSM DM prediction

[2014]



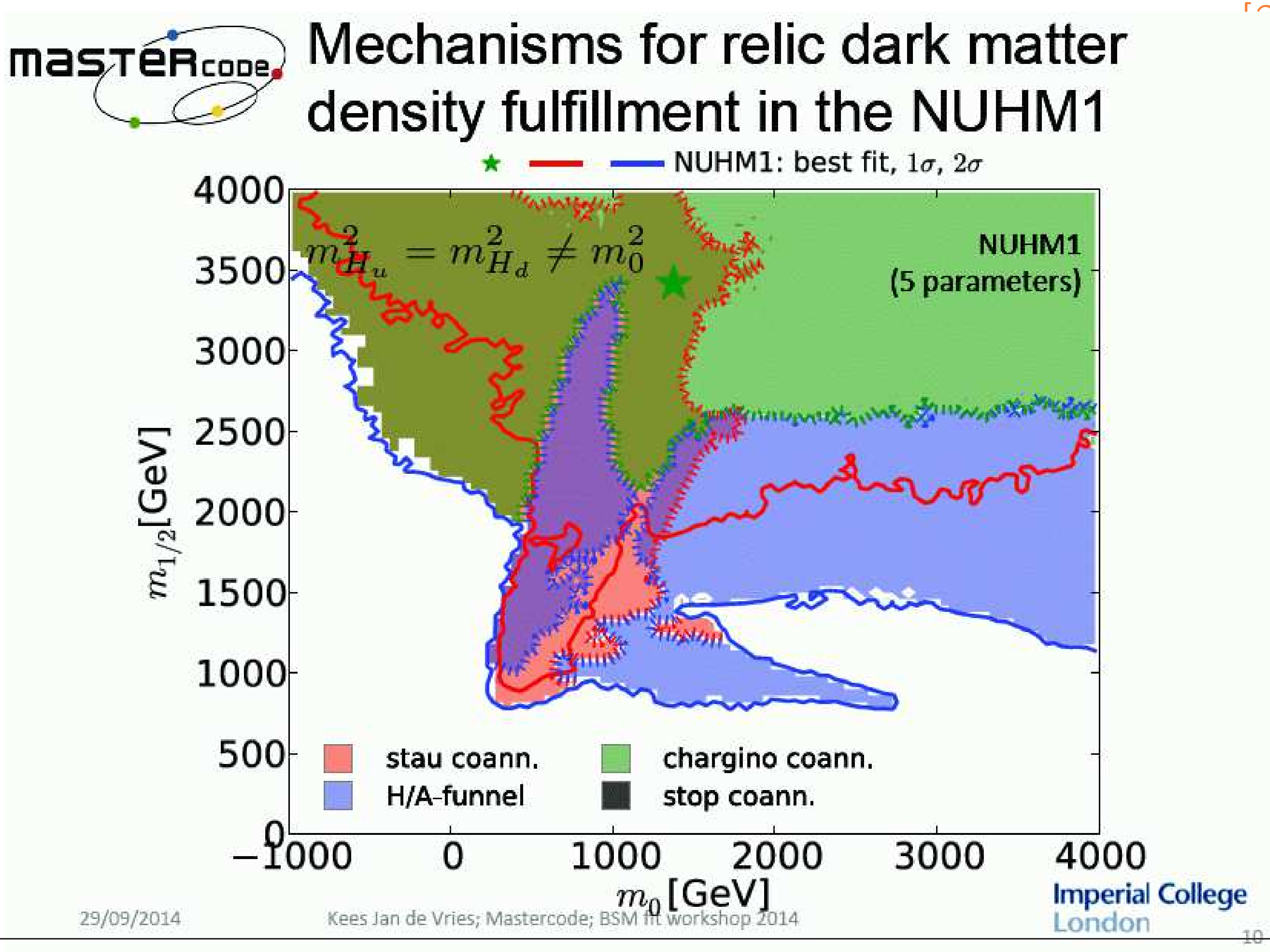
CMSSM DM prediction

[2014]



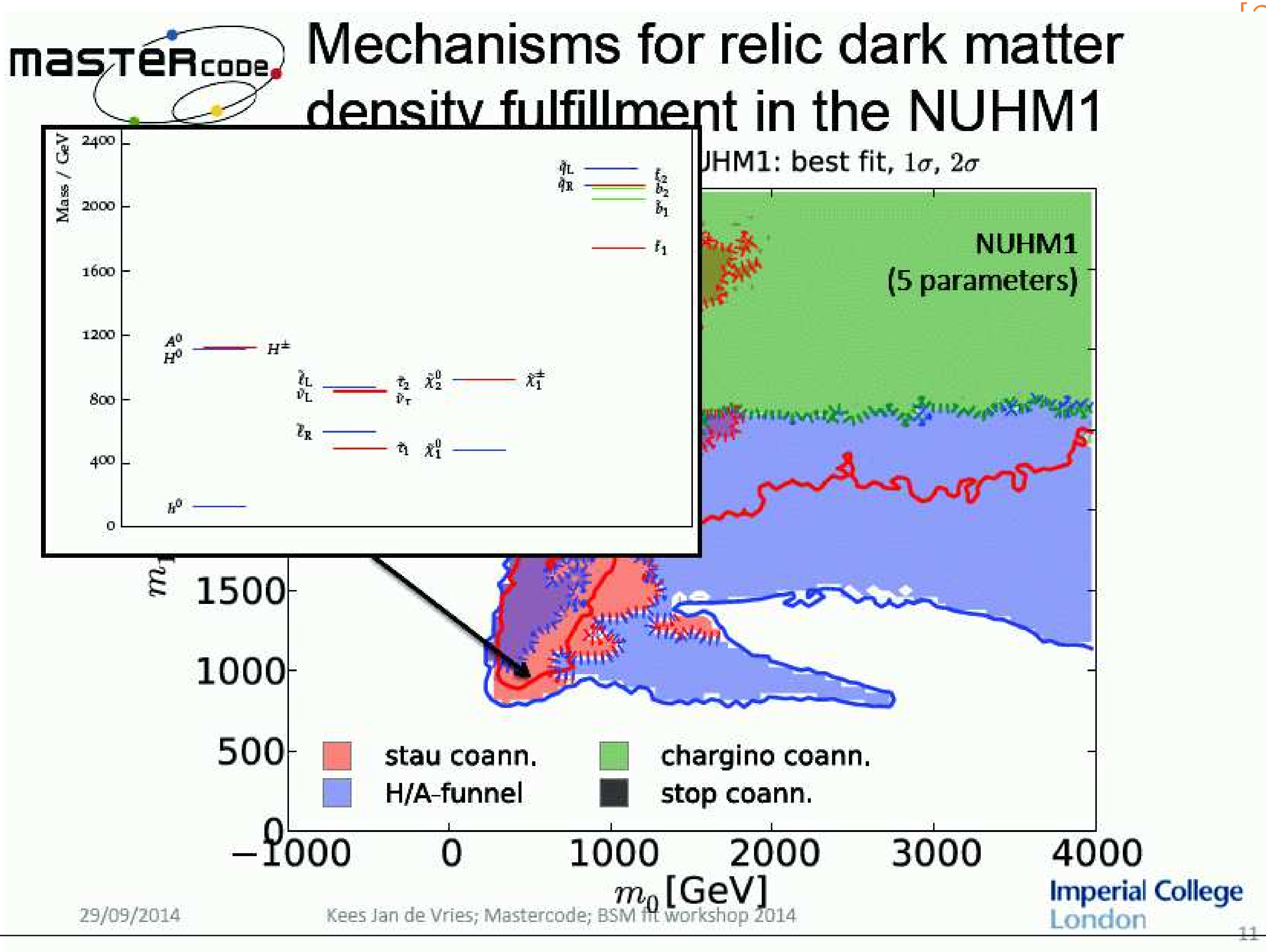
NUHM1 DM prediction

[2014]



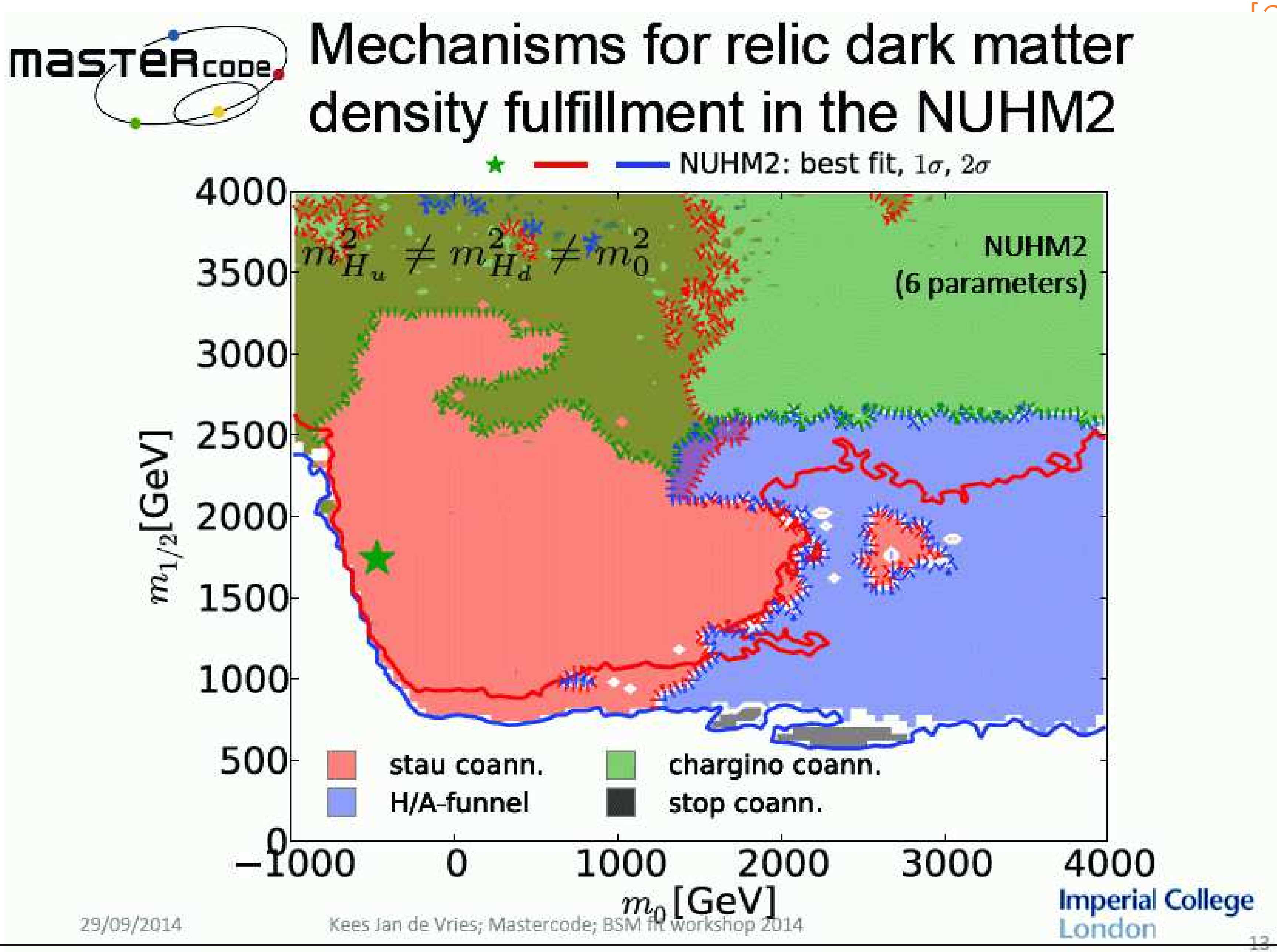
NUHM1 DM prediction

[2014]



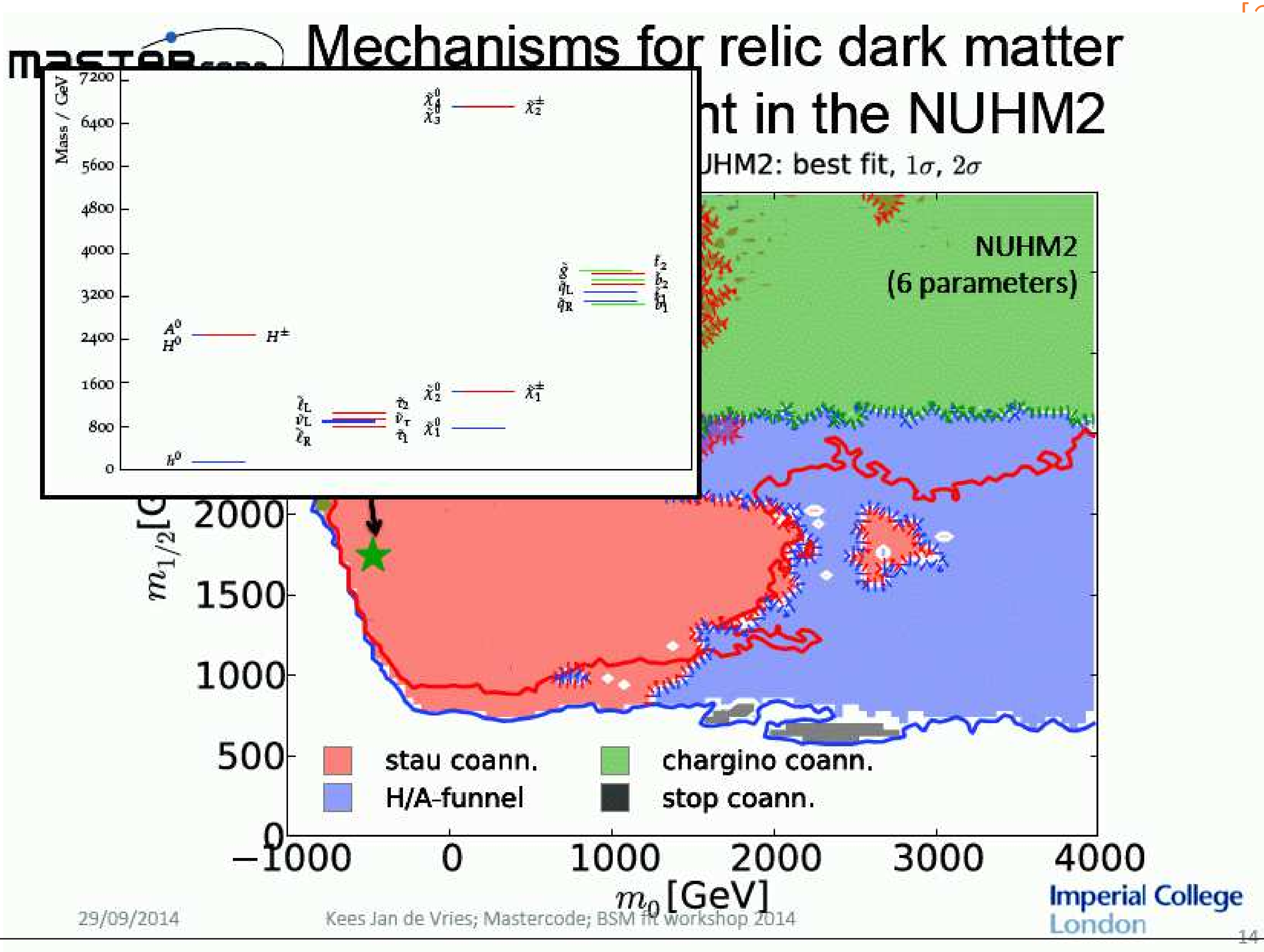
NUHM2 DM prediction

[2014]



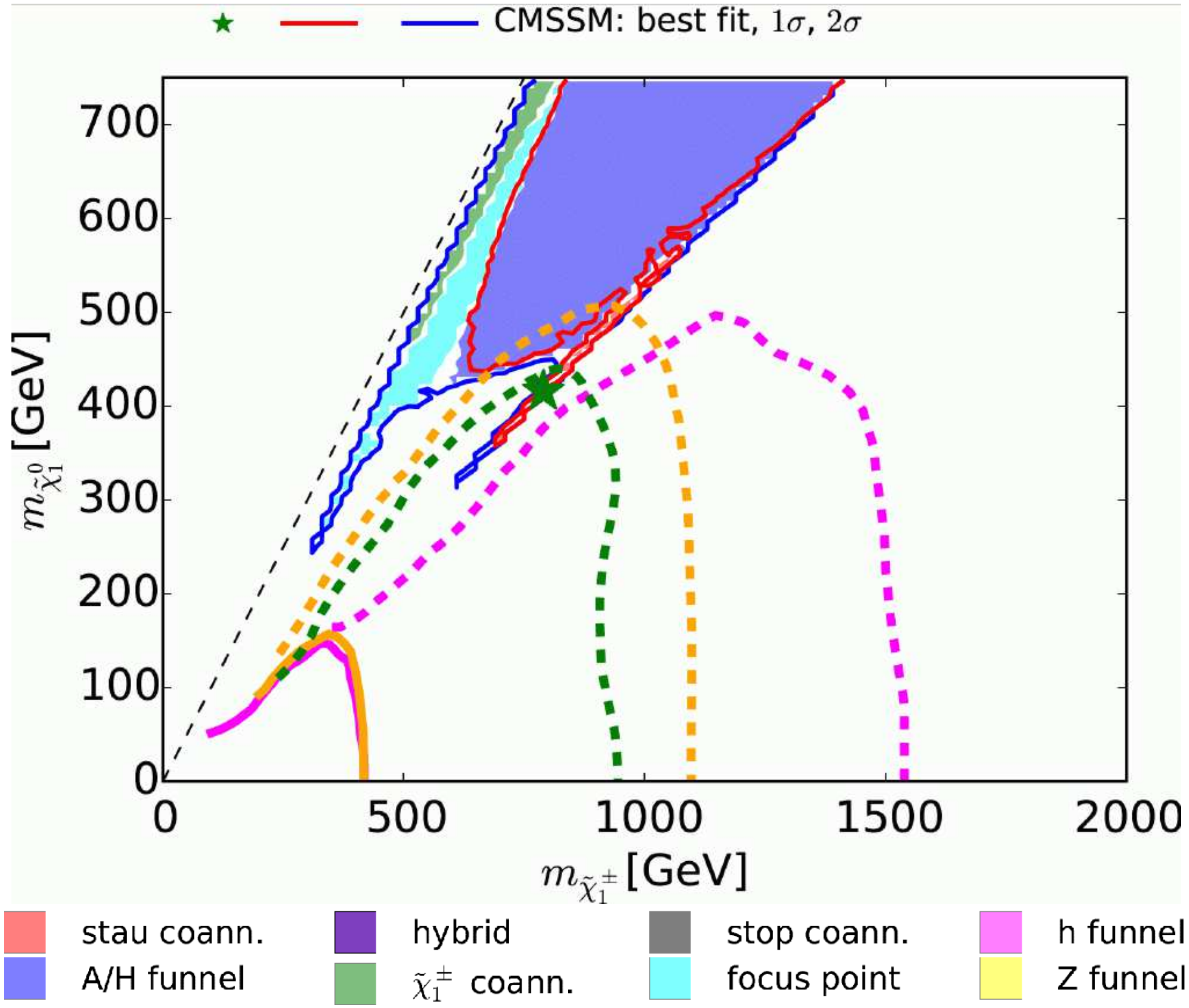
NUHM2 DM prediction

[?2014]



LHC prospects for CMSSM:

[2015]

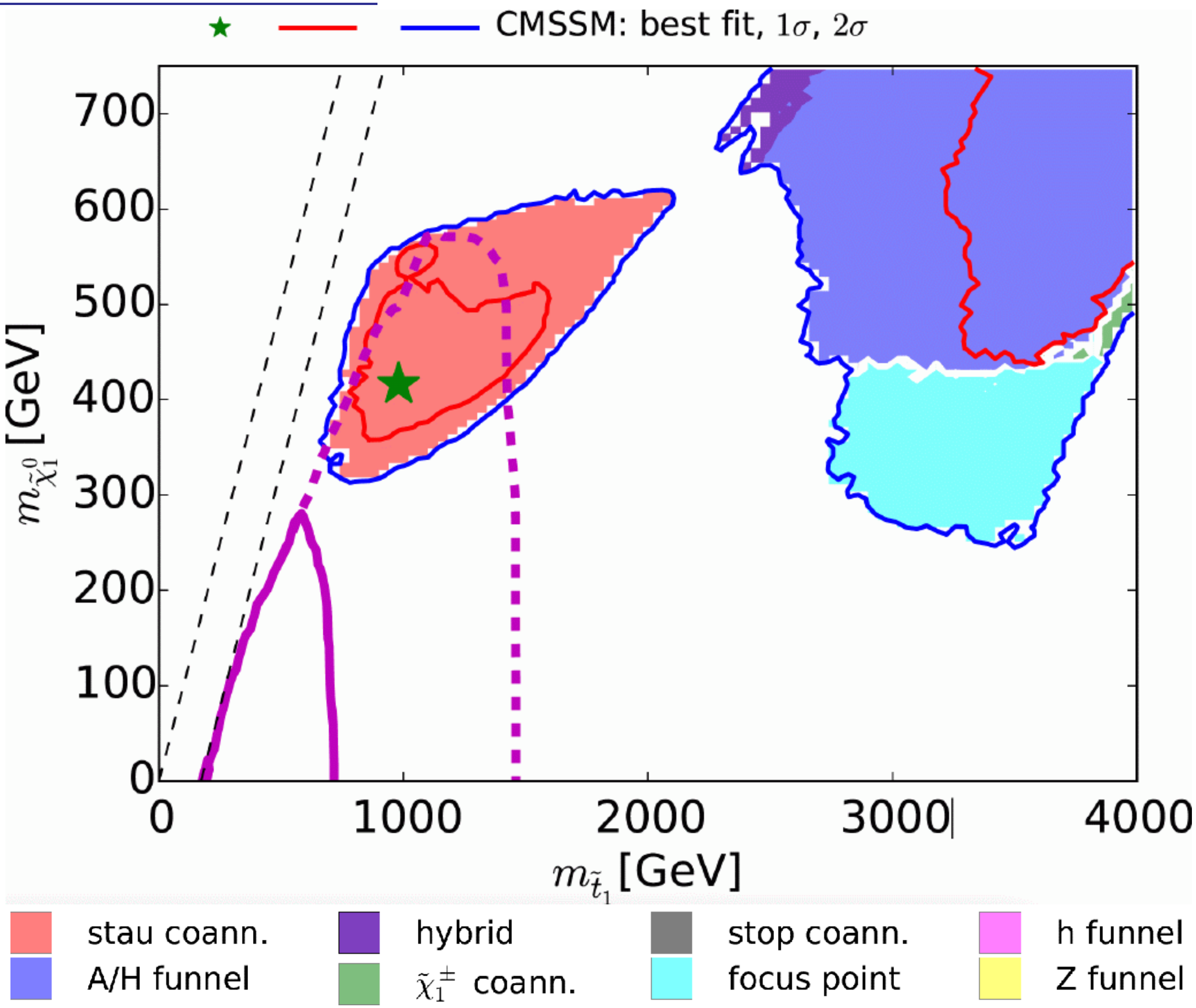


solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions can be covered! (in EW searches)

LHC prospects for CMSSM:

[2015]



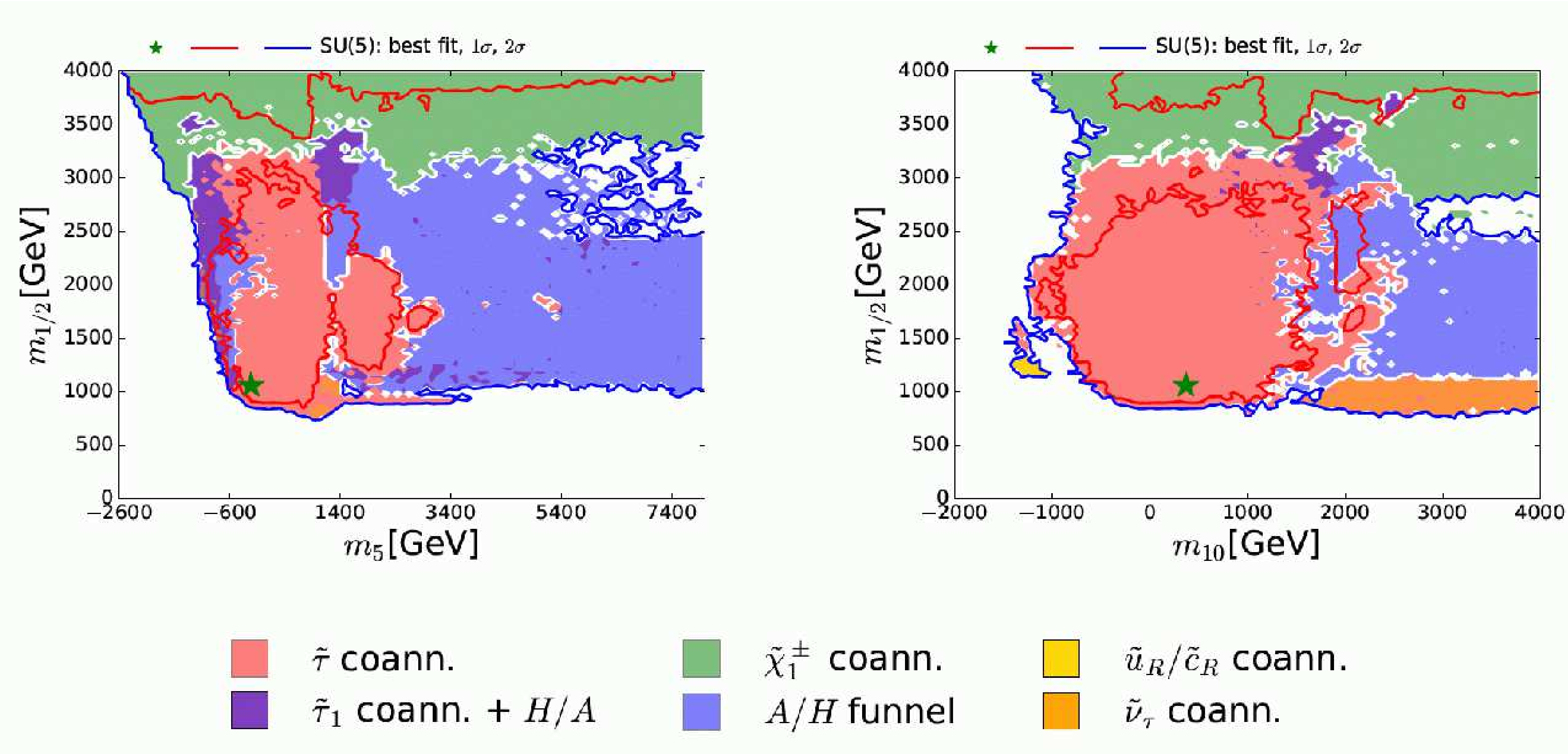
solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions can partially be covered! (in colored searches)

Results in the SU(5)

Dark Matter annihilation mechanism:

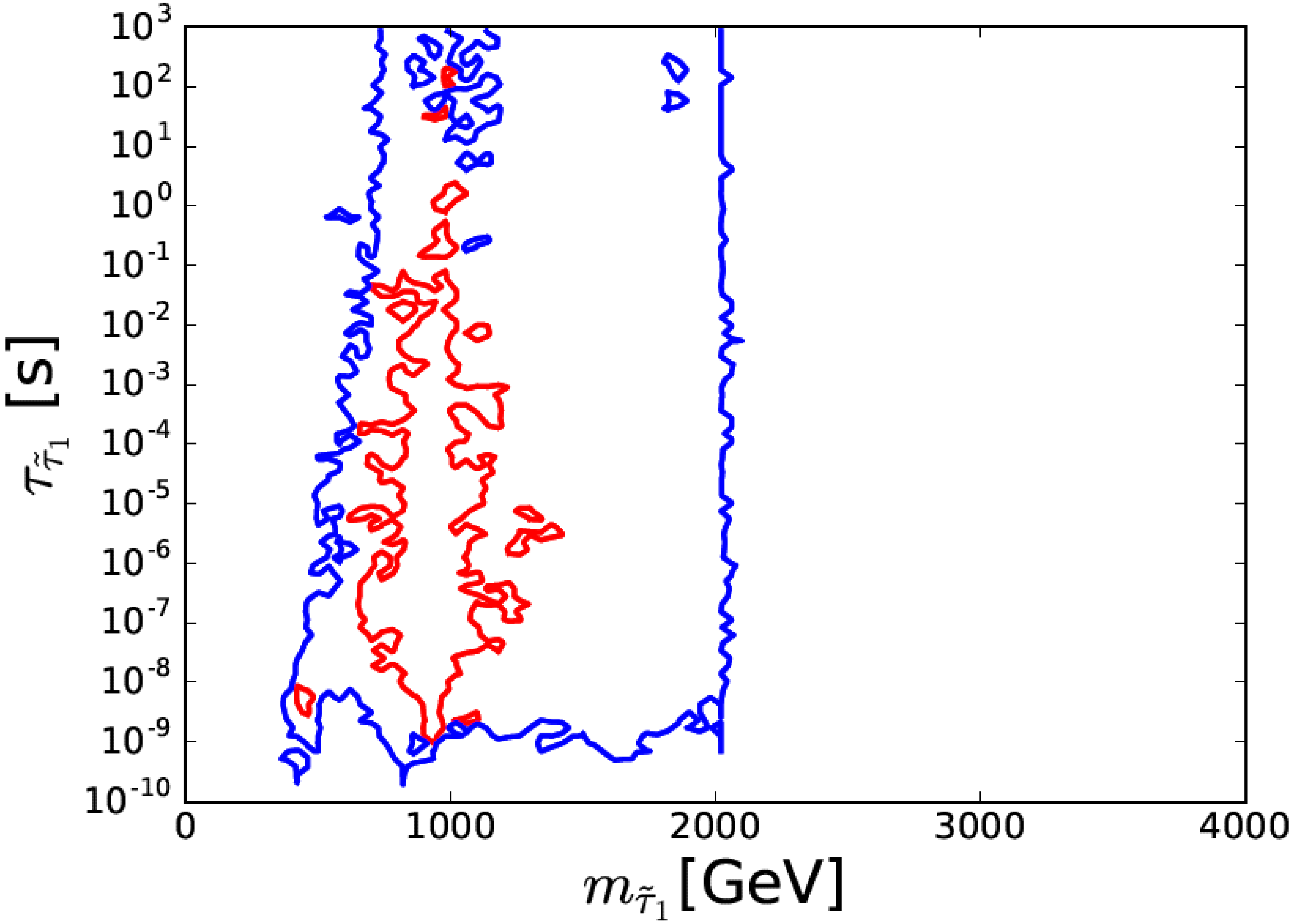
[2016]



$\Rightarrow \tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-ann. possible $\Rightarrow$ but $\tilde{\tau}_1$ co-ann. dominant!

NLSP stau searches at the LHC:

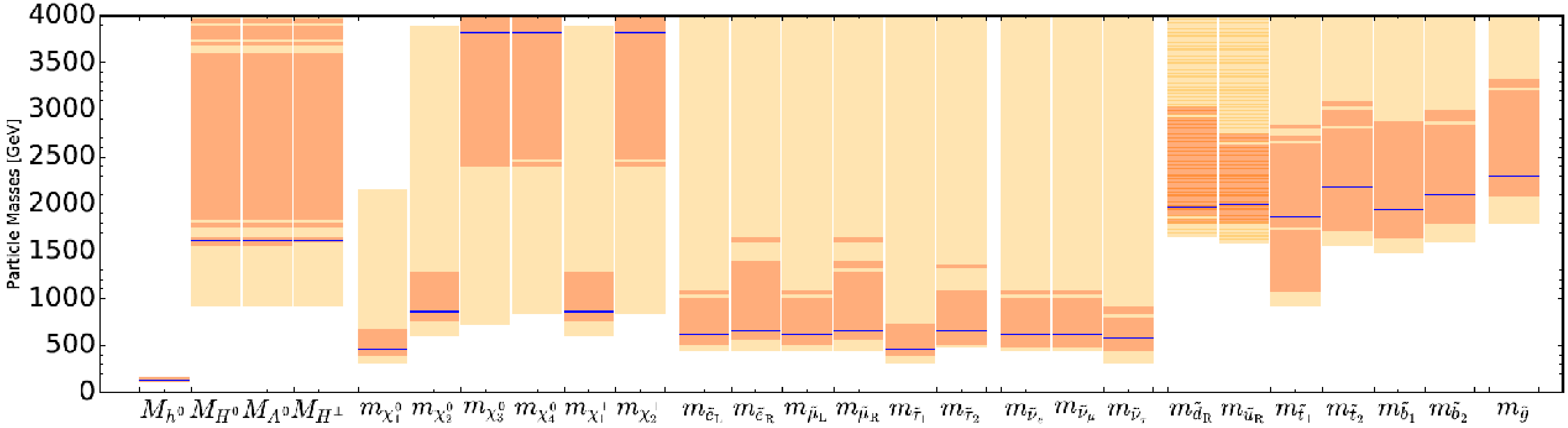
[2016]



$\Rightarrow$ search for long-lived staus!

SU(5) prediction: best-fit masses

[2016]



$\Rightarrow$ high colored masses

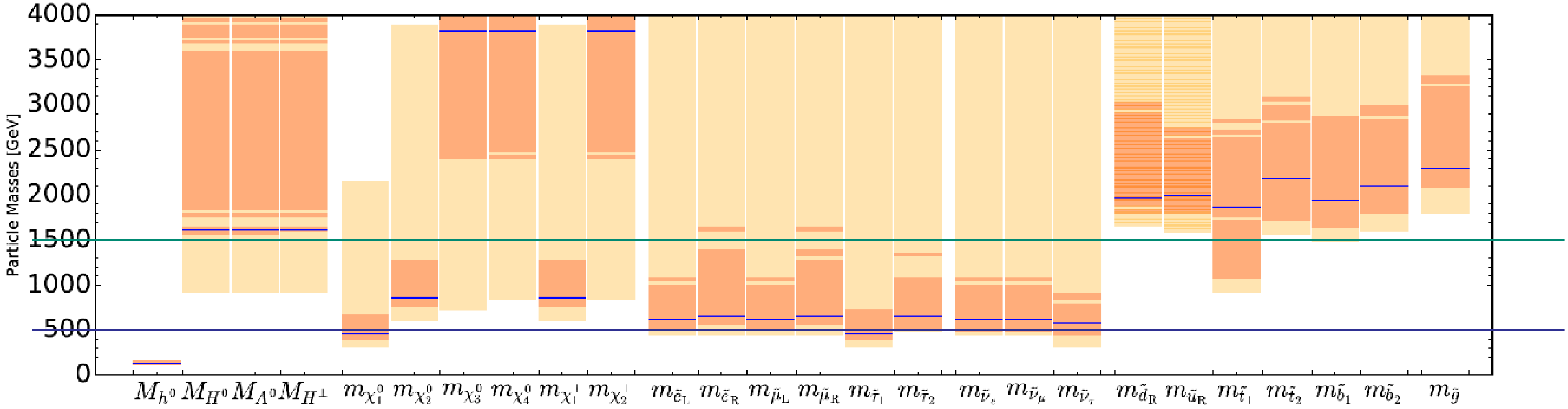
$\Rightarrow$ lower electroweak masses

partially with not too large $1\,\sigma$ ranges

$\Rightarrow$ clear prediction for ILC and CLIC

SU(5) prediction: best-fit masses

[2016]



ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ only few EW particles possibly accessible

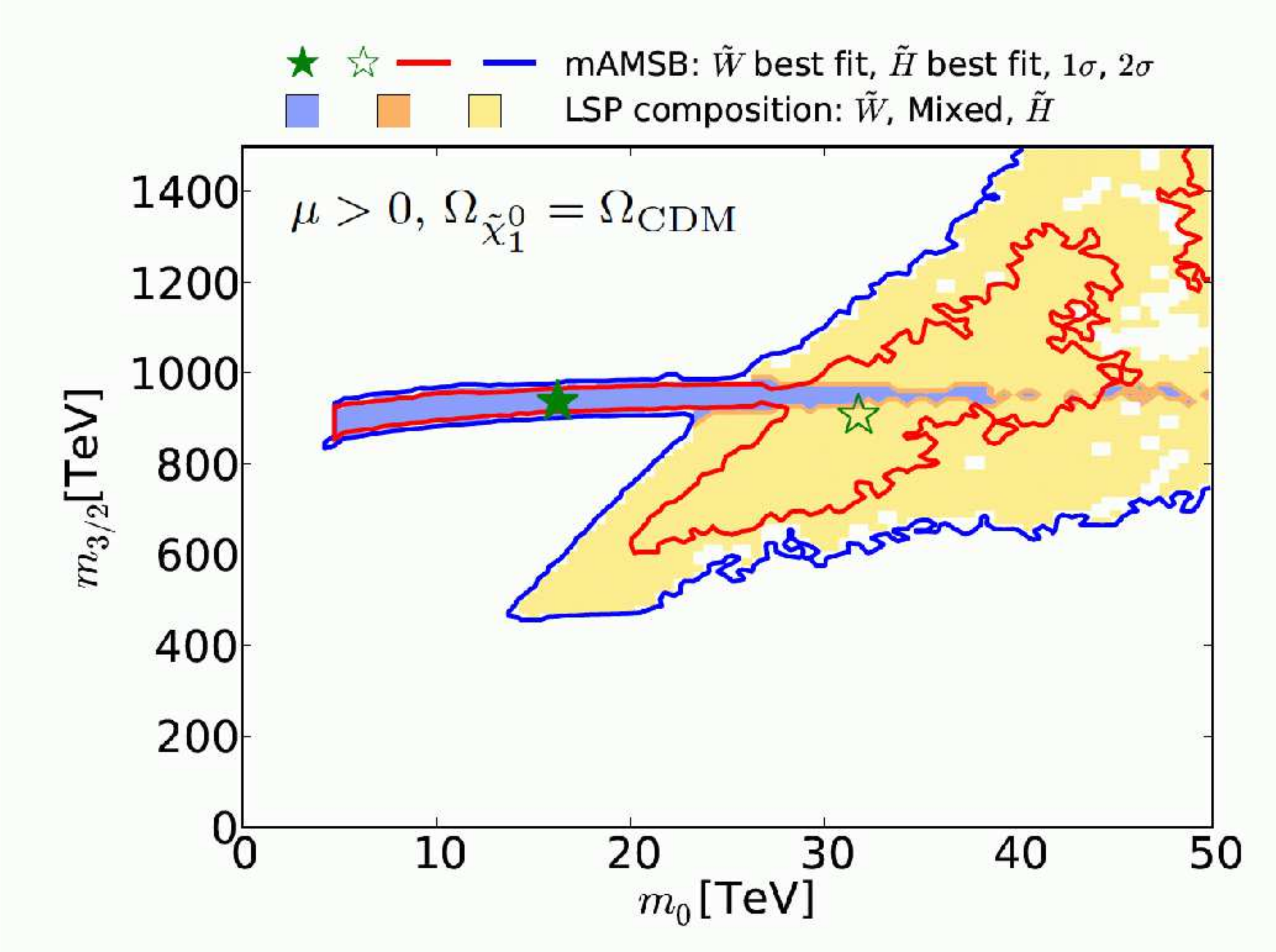
CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of many SUSY particles “likely”

$\Rightarrow$ no access to colored particles

Results in the mAMSB

[2016]

Dark Matter composition:

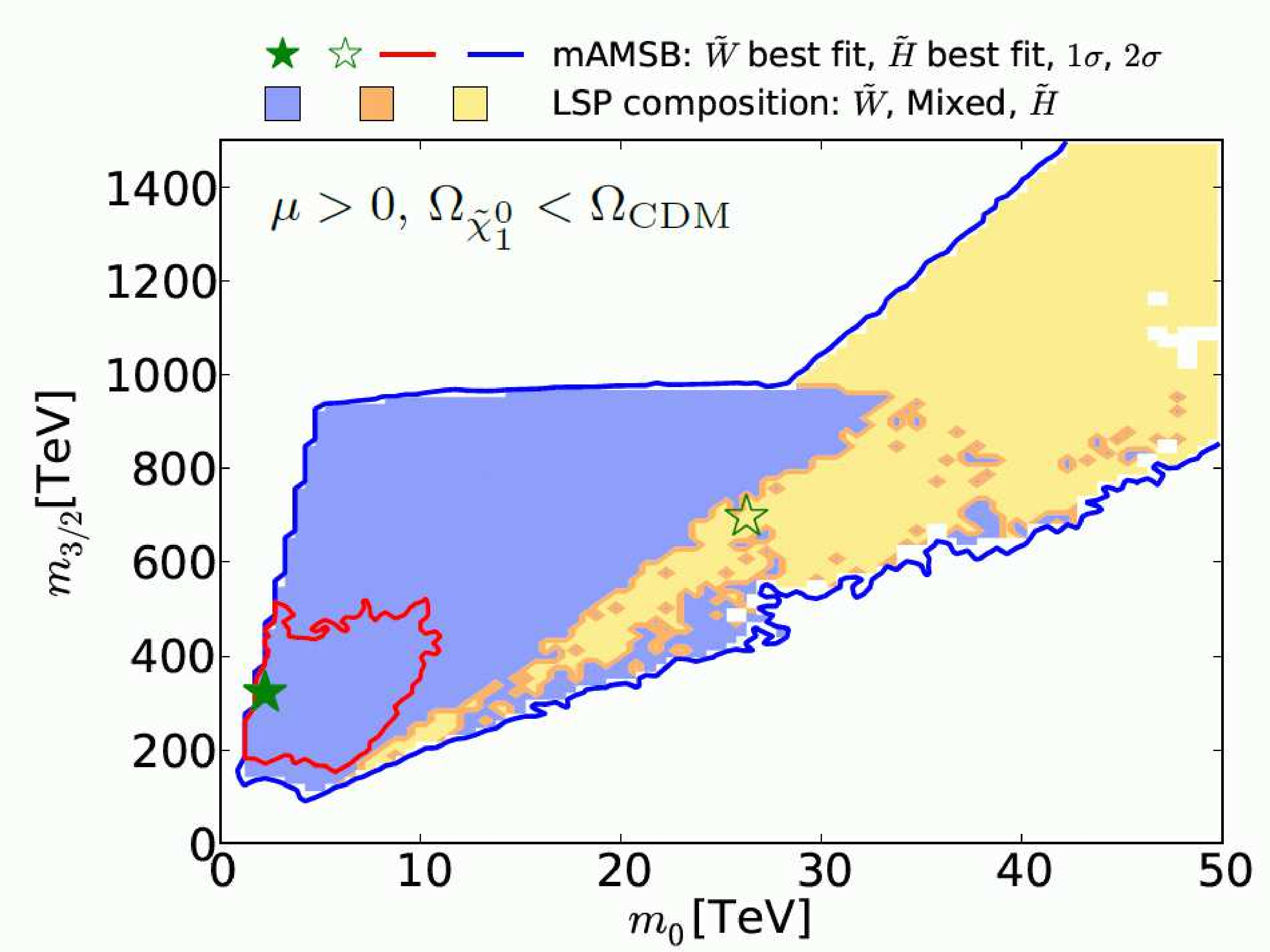


$\Rightarrow m_{\tilde{\chi}^0_1} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)

Results in the mAMSB

[2016]

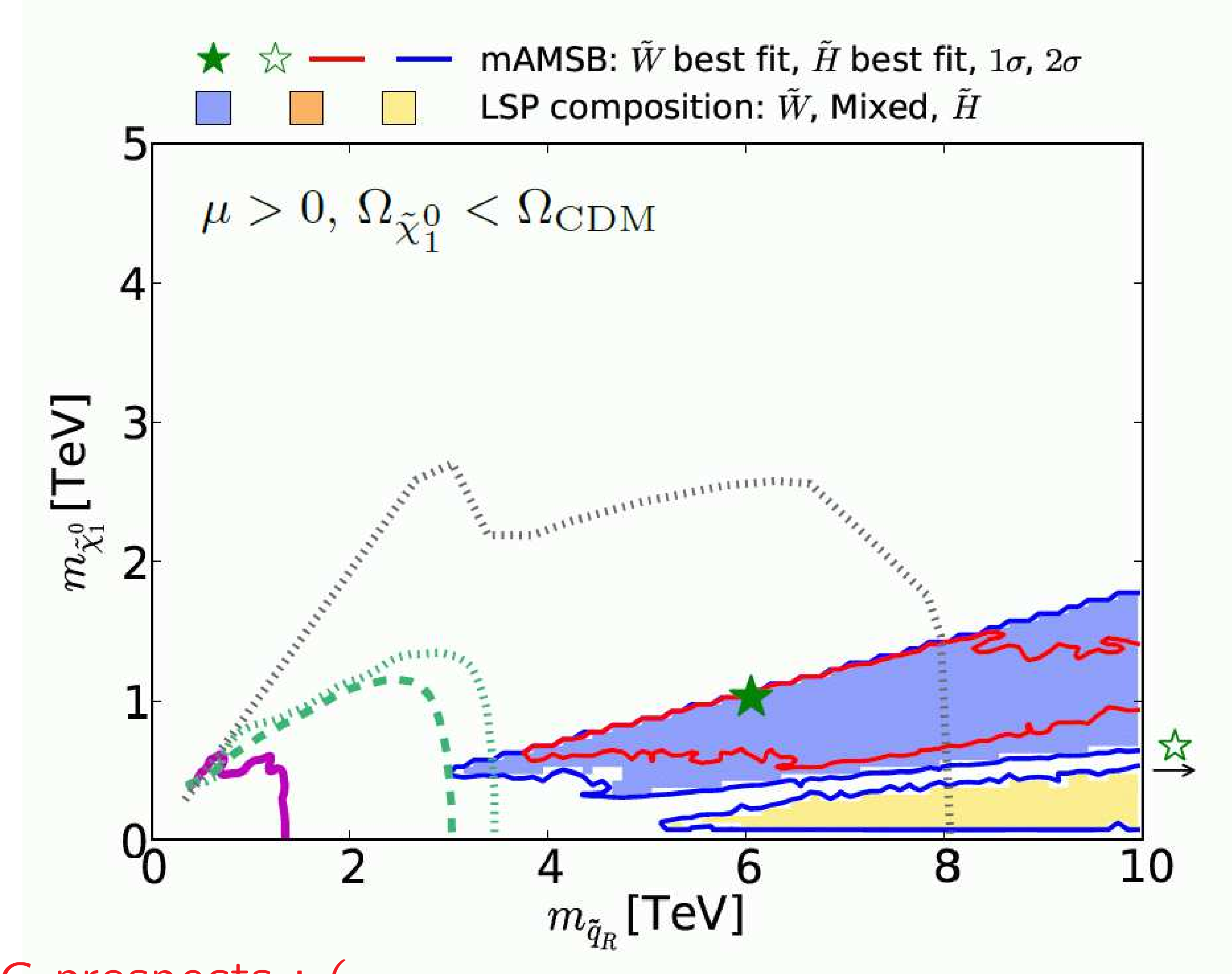
Dark Matter composition:



$\Rightarrow$ very relaxed limits $\Rightarrow$ lower masses

Squark mass vs. DM mass:

[2016]

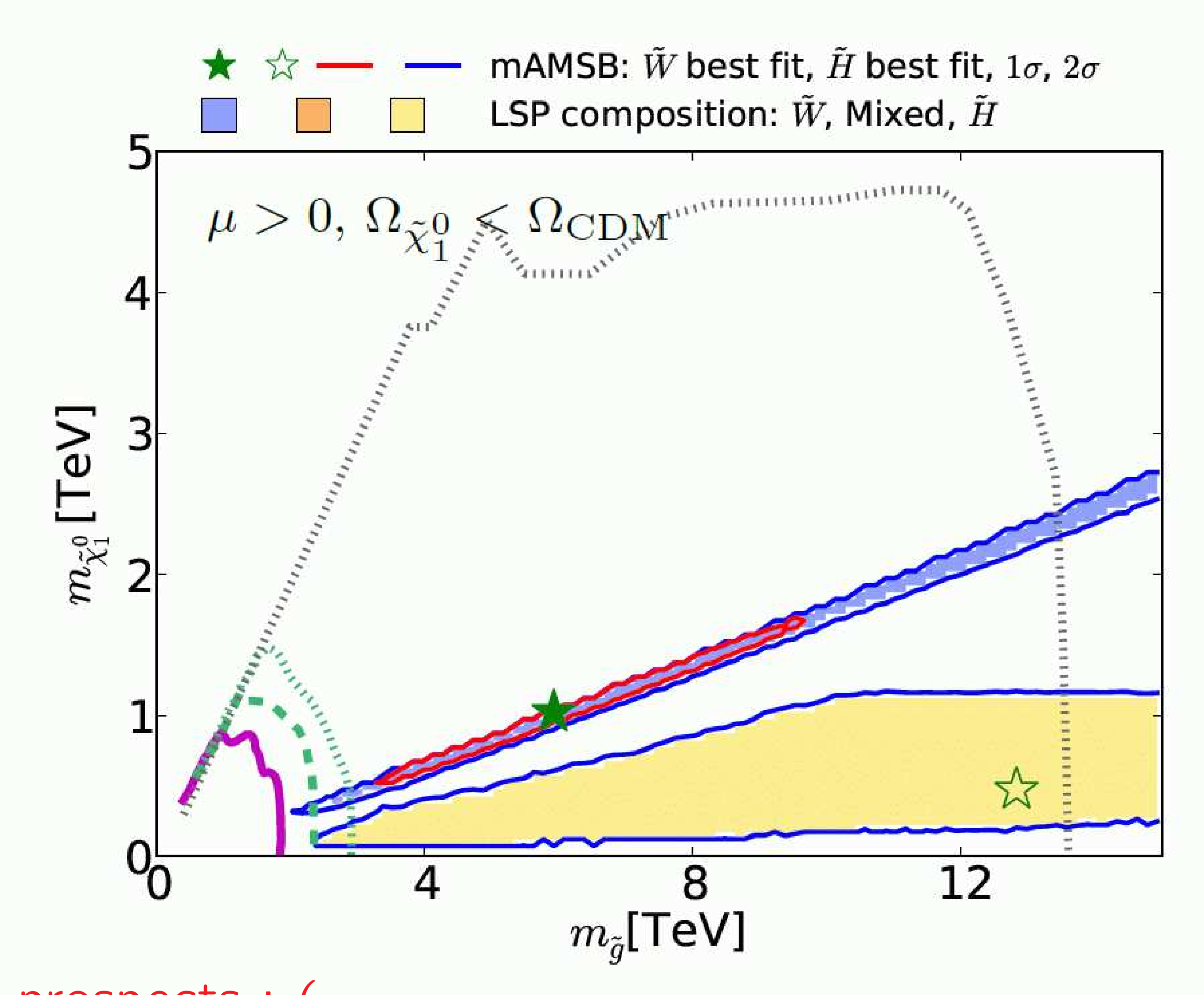


⇒ bad LHC prospects :-(

⇒ better FCC-hh prospects :-)

Gluino mass vs. DM mass:

[2016]

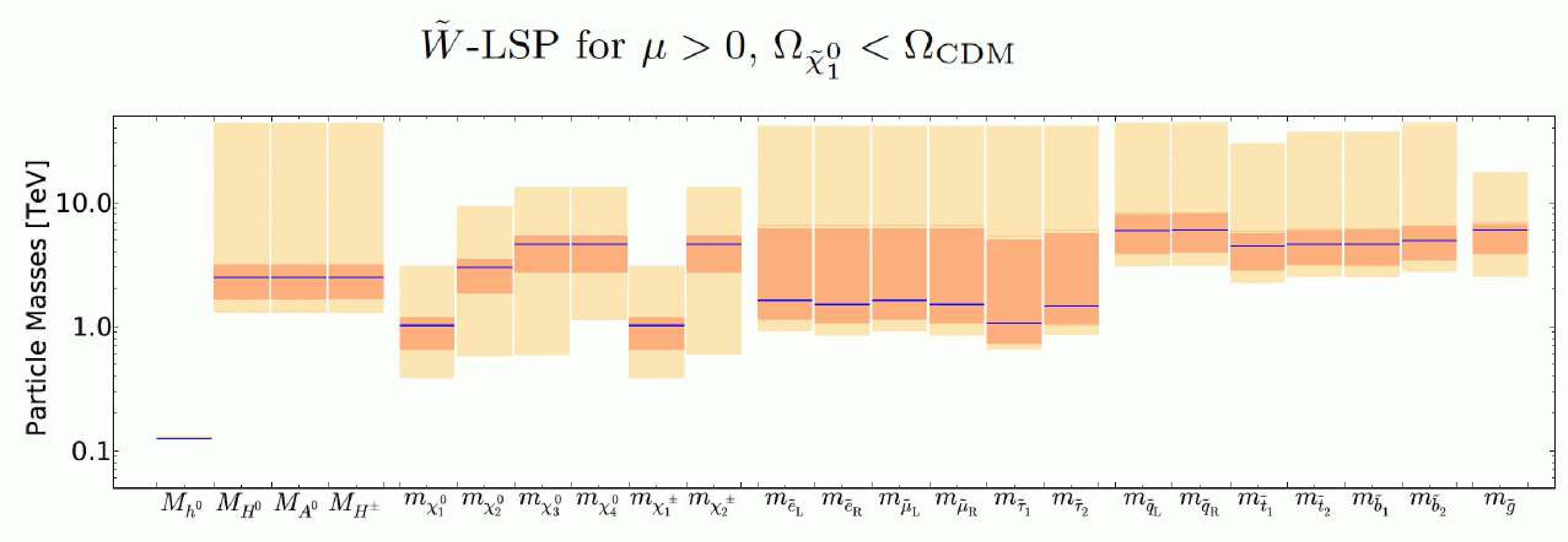


⇒ bad LHC prospects :-(

⇒ better FCC-hh prospects :-)

mAMSB prediction: best-fit masses (wino)

[2016]



$\Rightarrow$ high colored masses

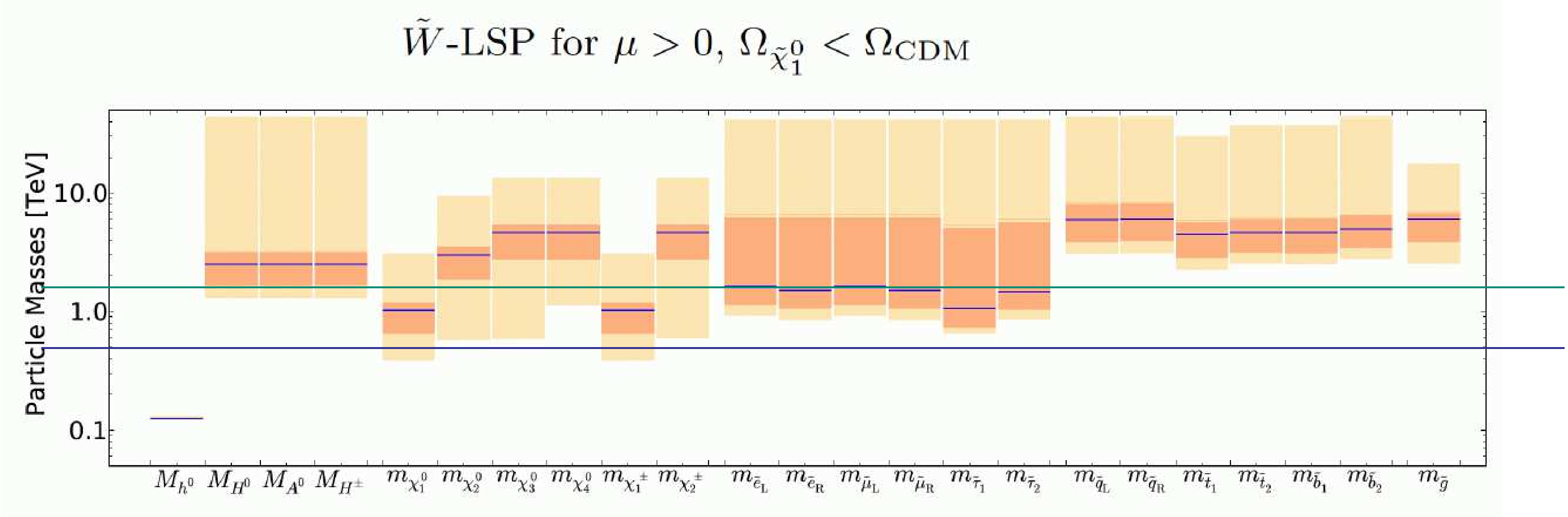
$\Rightarrow$ lower electroweak masses

partially with not too large $1\,\sigma$ ranges

$\Rightarrow$ clear prediction for ILC and CLIC

mAMSB prediction: best-fit masses (wino)

[2016]

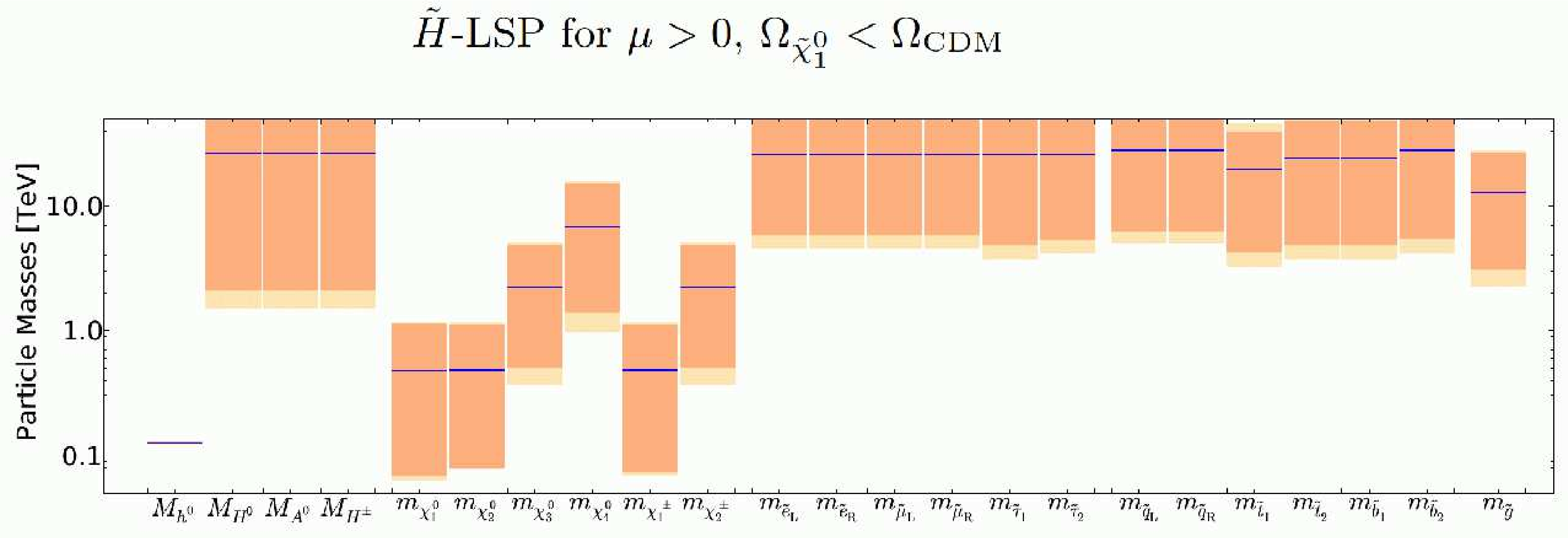


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ bad prospects

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of few SUSY particles "likely"
$\Rightarrow$ no access to colored particles

mAMSB prediction: best-fit masses (higgsino)

[2016]



$\Rightarrow$ high colored masses

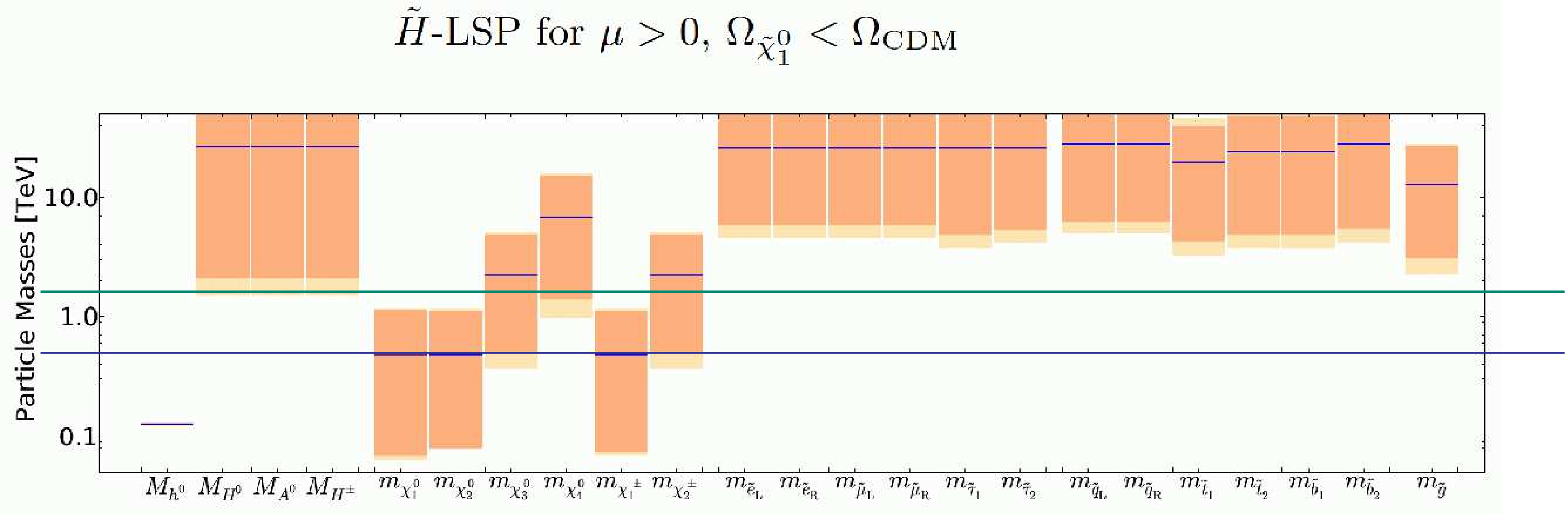
$\Rightarrow$ some(!) lower electroweak masses

partially with not too large 2σ ranges

$\Rightarrow$ clear prediction for ILC and CLIC

mAMSB prediction: best-fit masses (higgsino)

[2016]



ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ few EW particles possibly accessible

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of few SUSY particles "gurananteed"

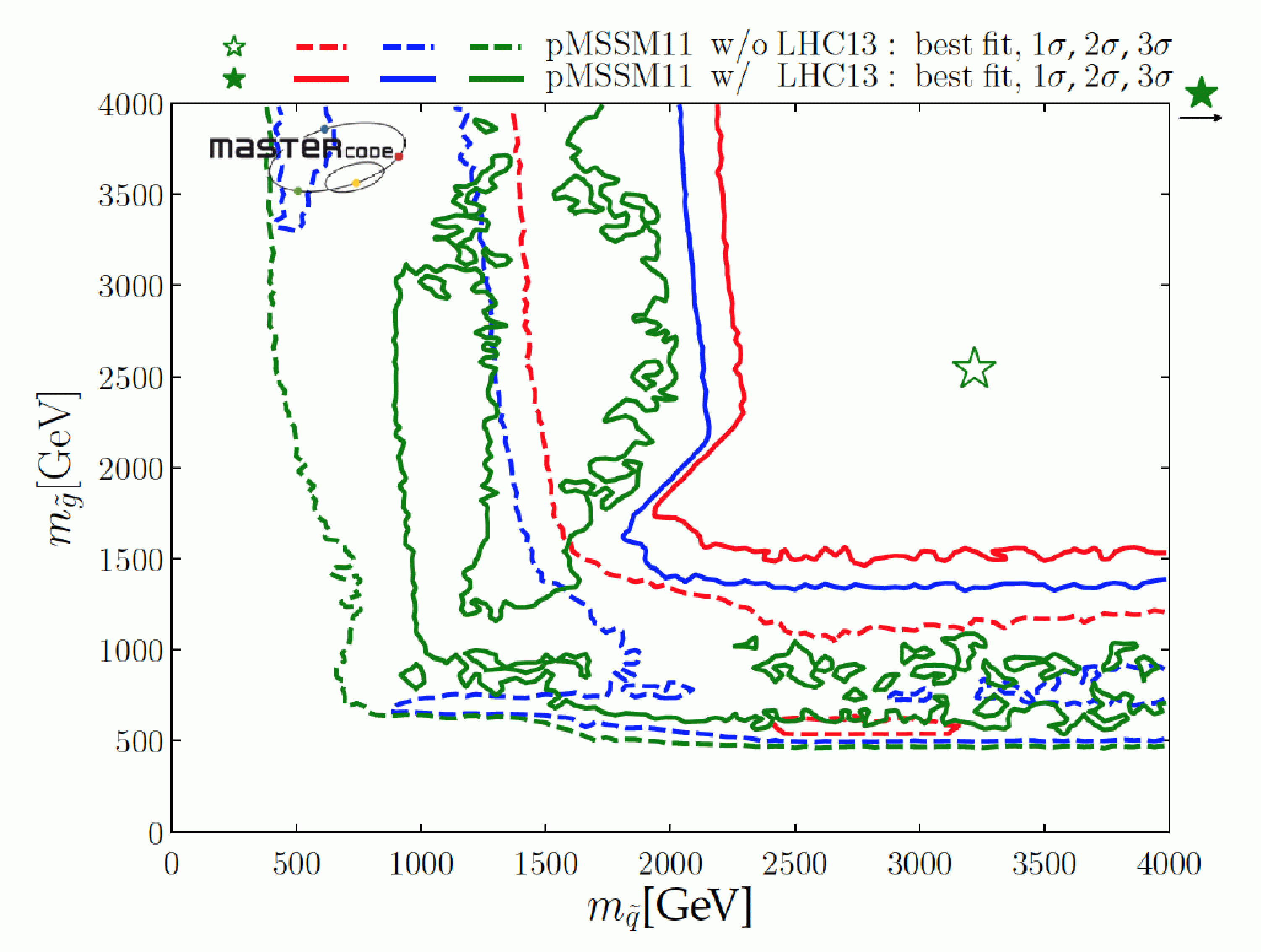
$\Rightarrow$ no access to colored particles

3. Results and predictions in the pMSSM11

Parameter	Range	Number of segments
M_1	(-4 , 4) TeV	6
M_2	(0 , 4) TeV	2
M_3	(-4 , 4) TeV	4
$m_{\tilde{q}}$	(0 , 4) TeV	2
$m_{\tilde{q}3}$	(0 , 4) TeV	2
$m_{\tilde{l}}$	(0 , 2) TeV	1
$m_{\tilde{\tau}}$	(0 , 2) TeV	1
M_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan\beta$	(1 , 60)	1
Total number of boxes		384

pMSSM11: Going from 8 TeV to 13 TeV (and adding latest DM limits)

[2017]

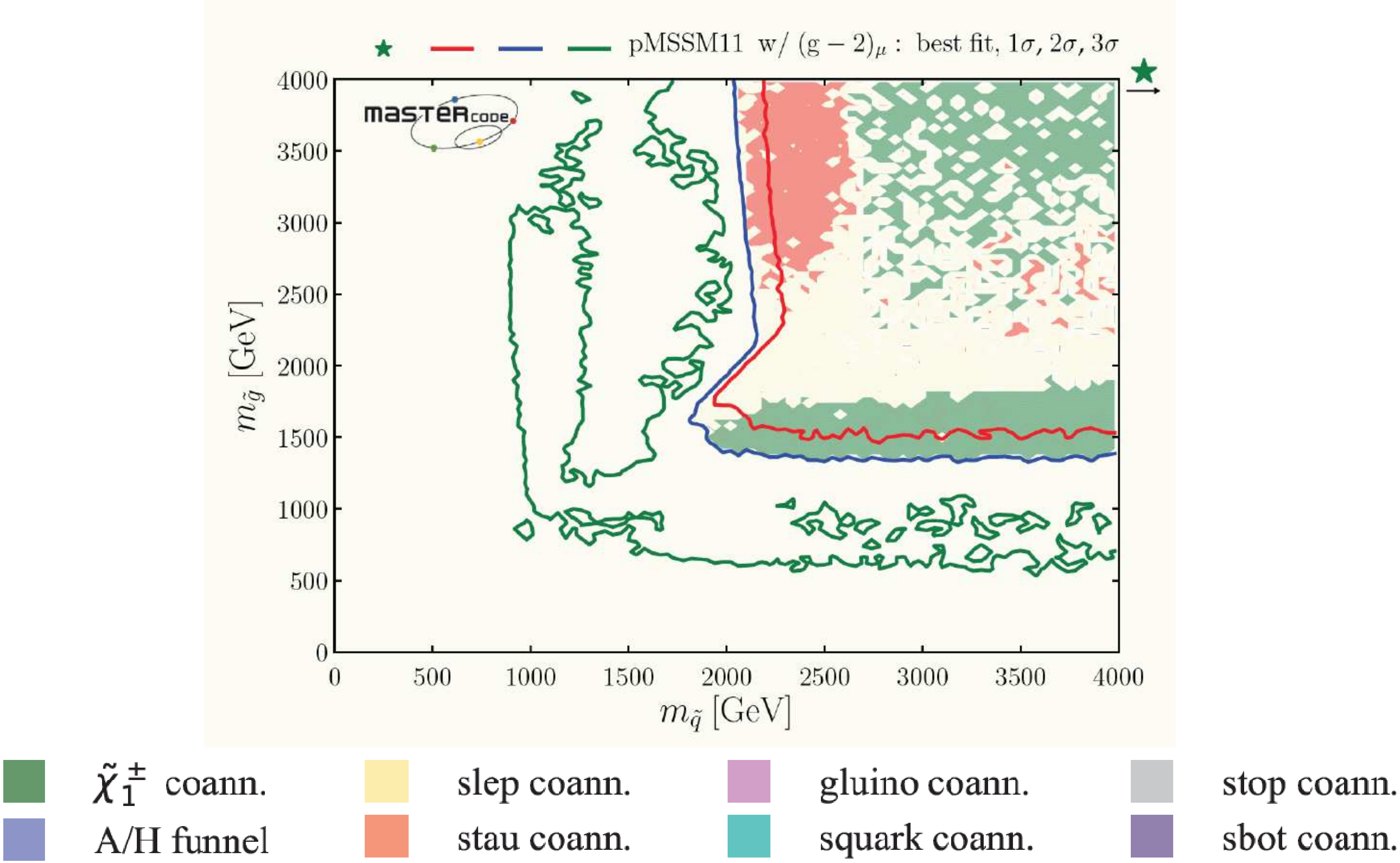


⇒ substantial move to higher masses!

⇒ notice the "nose"!

pMSSM11: $m_{\tilde{q}}$–$m_{\tilde{g}}$ plane

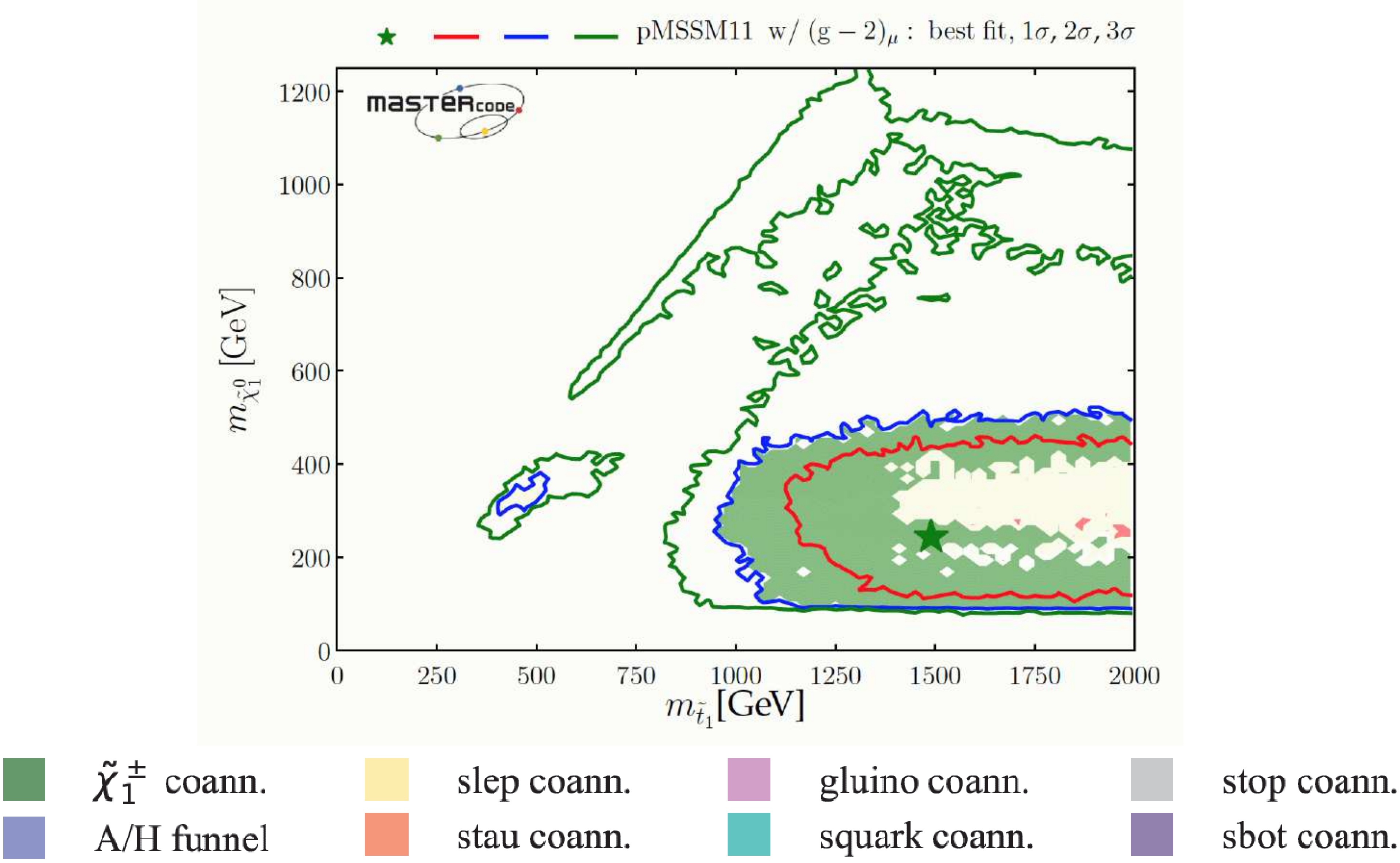
[2017]



$\Rightarrow$ high masses favored

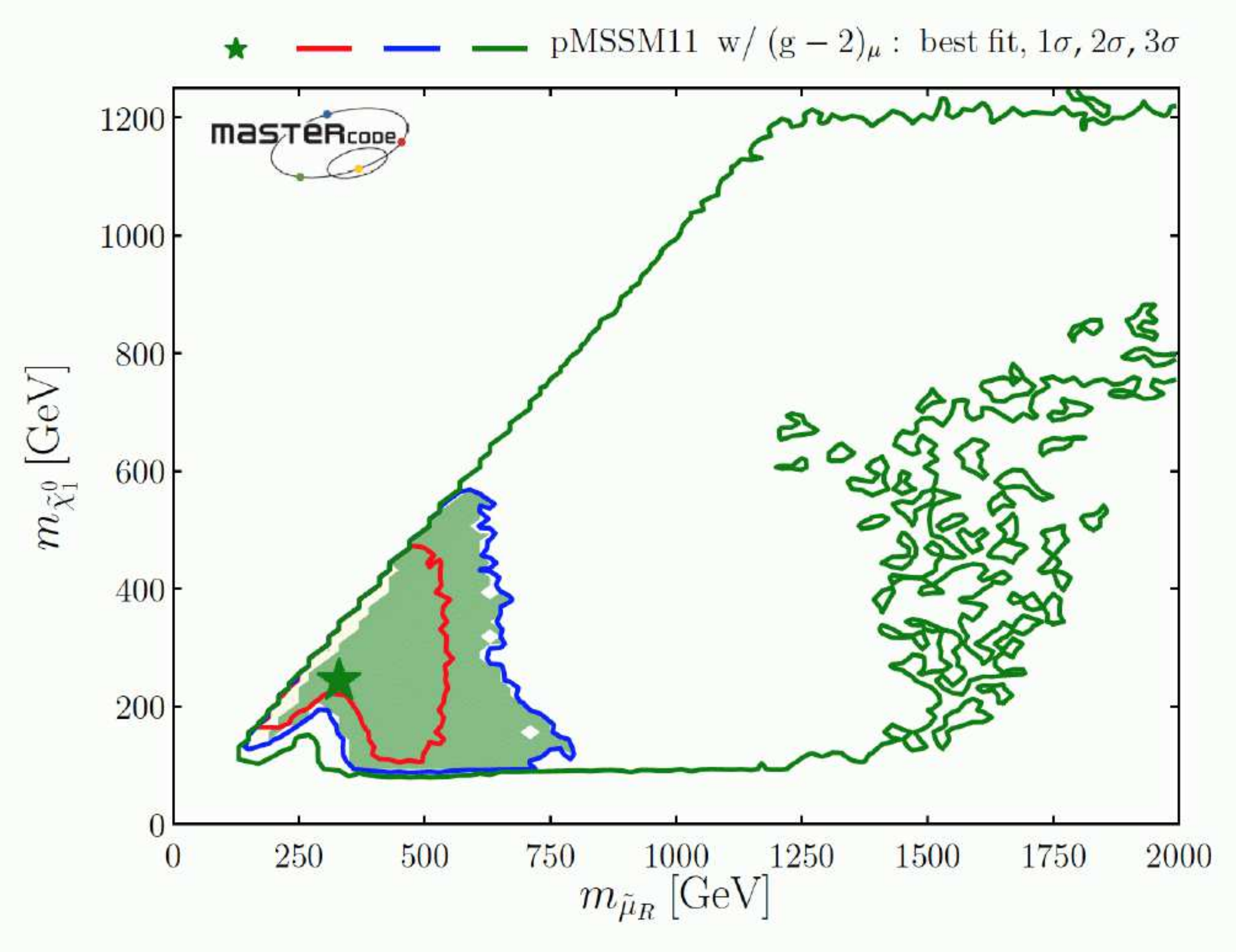
$\Rightarrow$ notice the "nose"!

pMSSM11: $m_{\tilde{t}_1}$–$m_{\tilde{\chi}^0_1}$ plane



$\Rightarrow$ high (low) stop (neutralino) masses $\Rightarrow$ notice the compressed region!

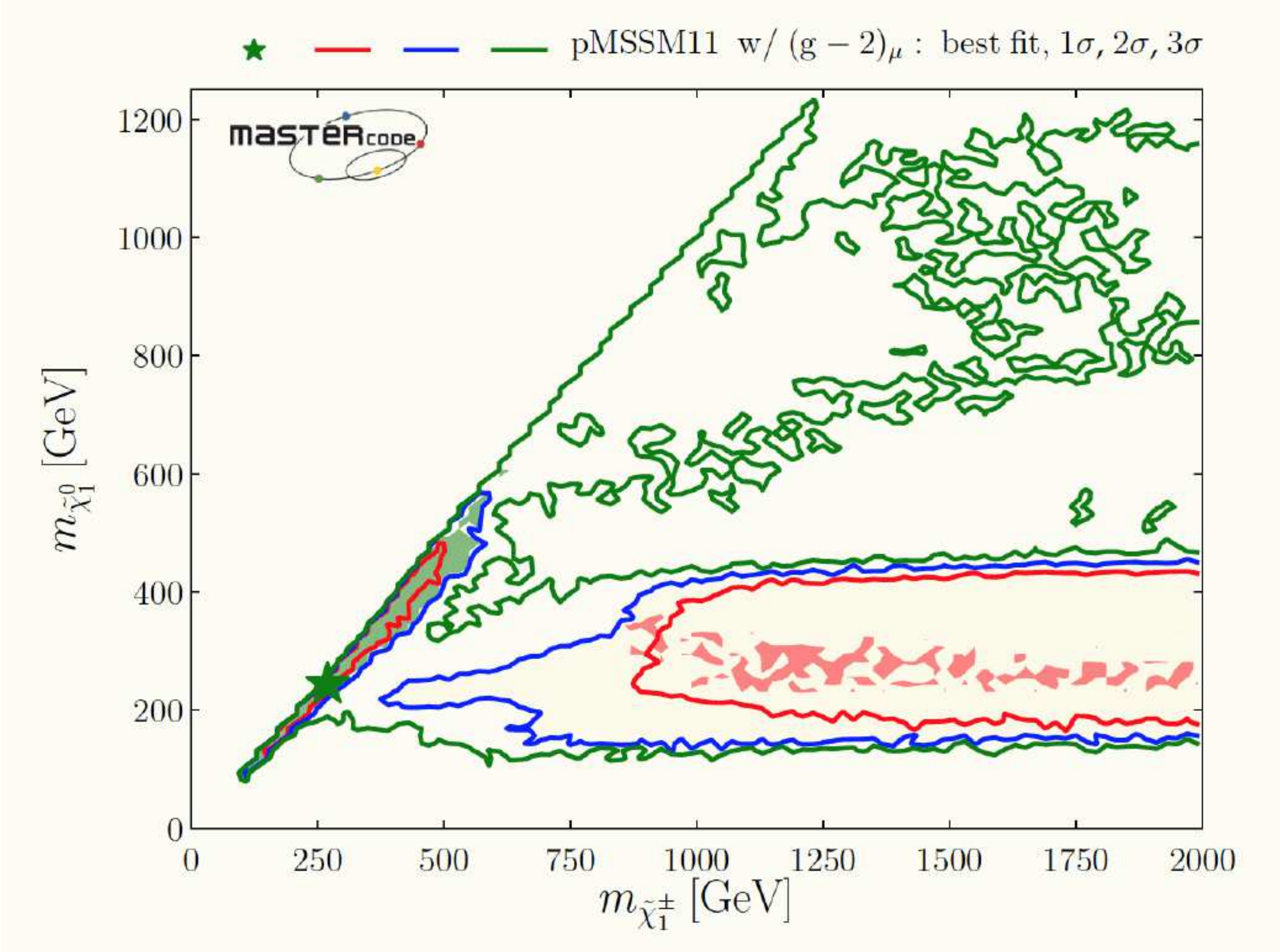
pMSSM11: $m_{\tilde{\mu}}$–$m_{\tilde{\chi}_1^0}$ plane



$\Rightarrow$ all masses low!!

pMSSM11: $m_{\tilde{\chi}_1^\pm}$–$m_{\tilde{\chi}_1^0}$ planbe

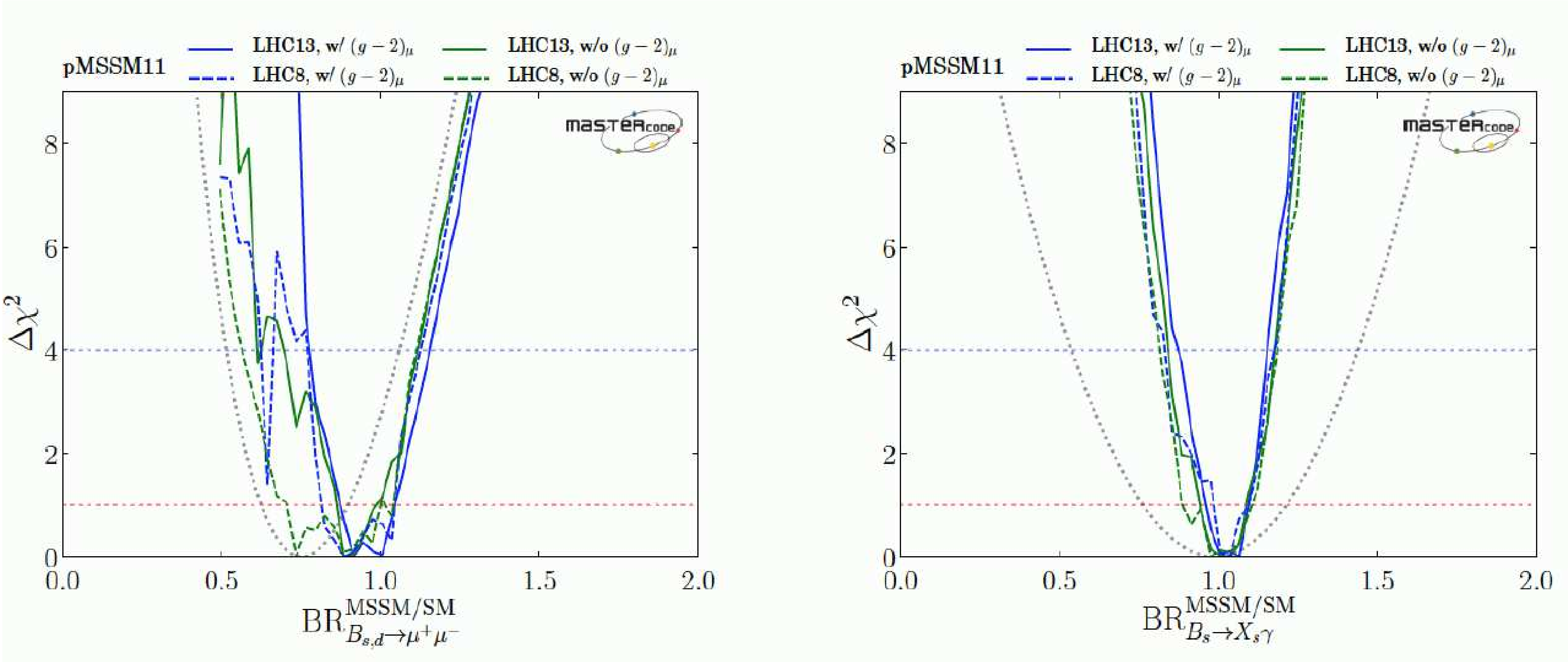
[2017]



$\Rightarrow$ chargino co-annihilation $\Rightarrow M_1 \sim M_2$

pMSSM11: B physics observables

[2017]

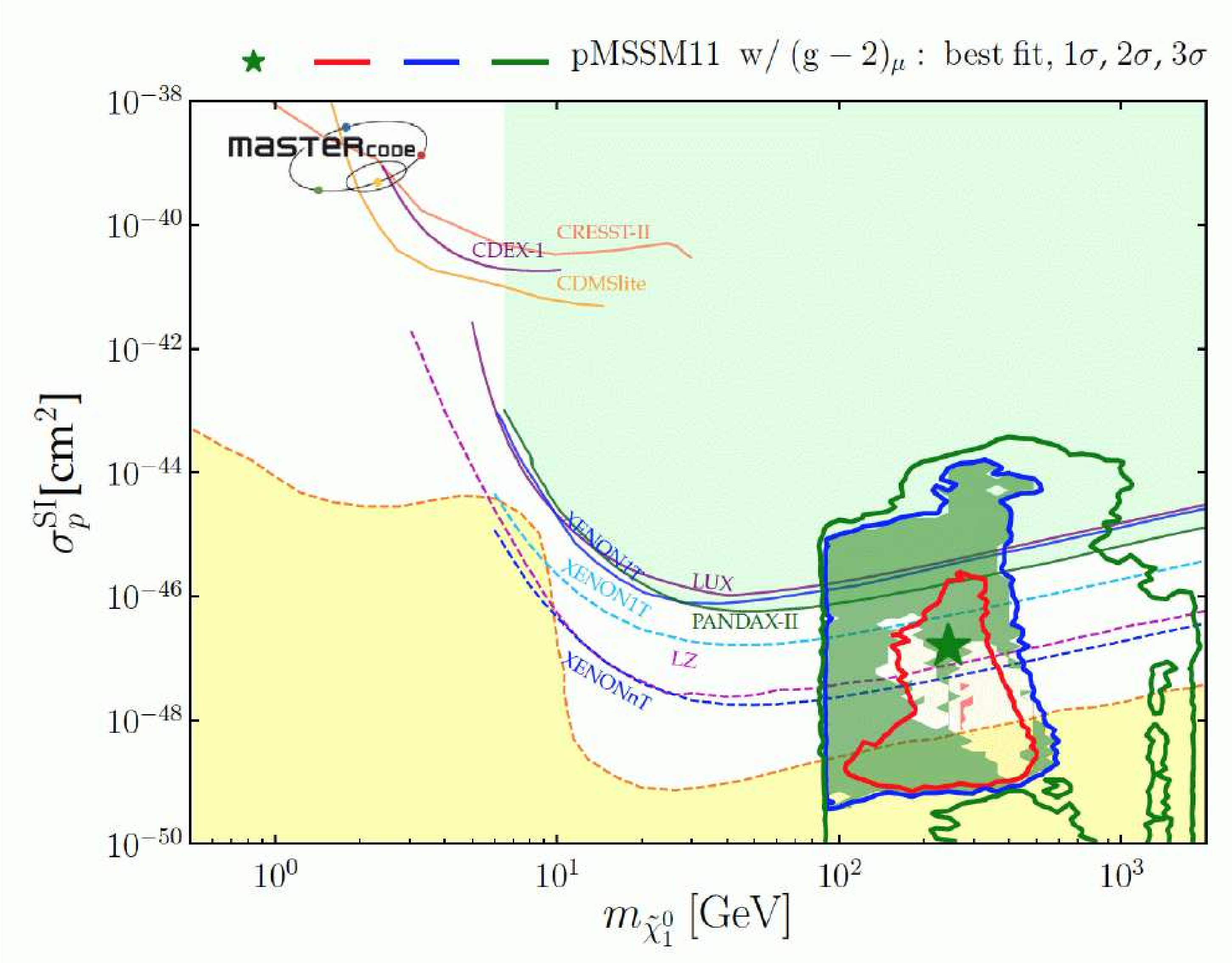


$\Rightarrow$ follows the experimental data

$\Rightarrow$ BR($B_s \to \mu^+\mu^-$): below the SM value

pMSSM11: DM predictions

[2017]



$\Rightarrow$ good prospects for future experiments $\Rightarrow$ but no guarantee

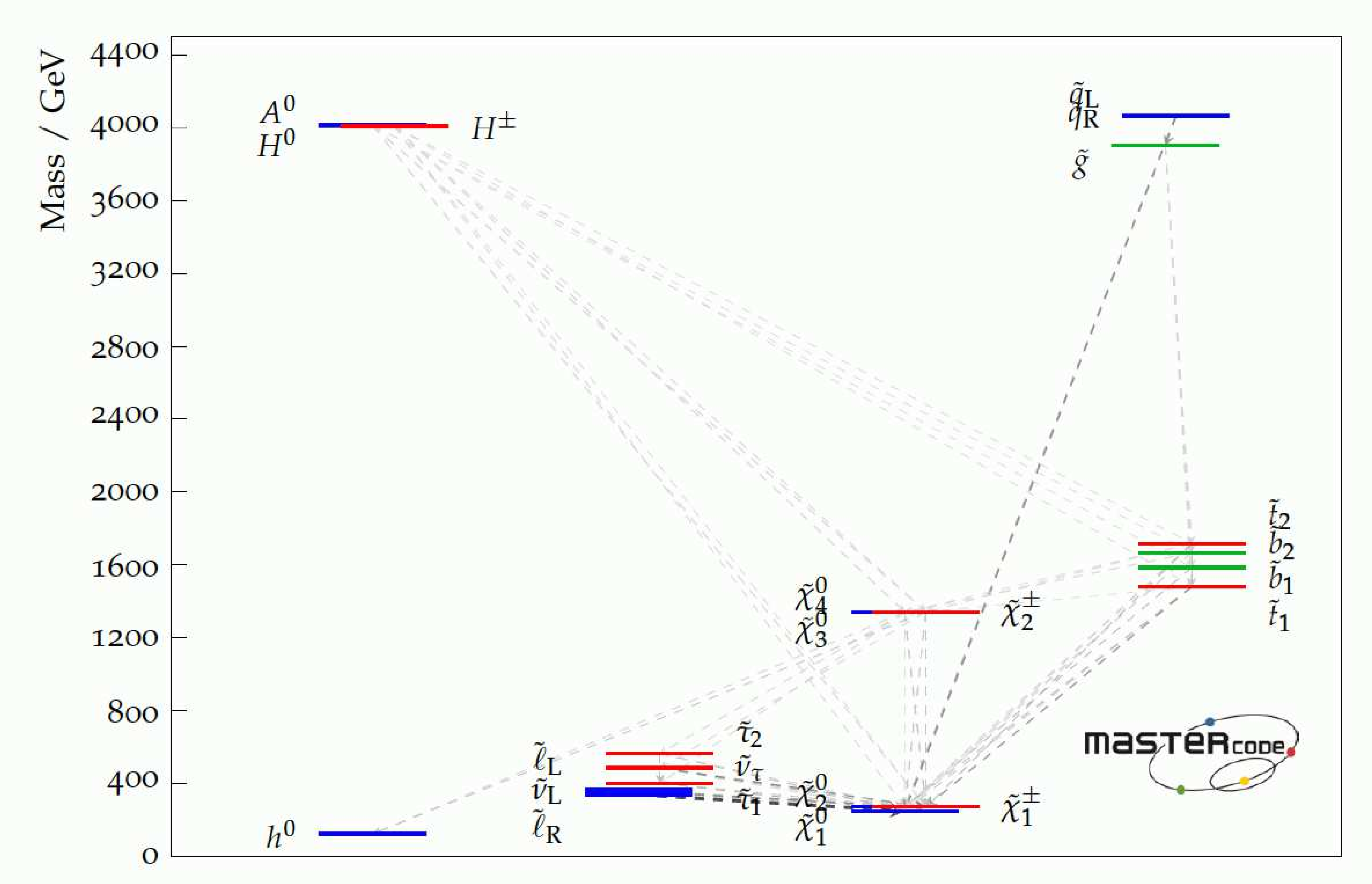
pMSSM11: best-fit point parameters

[2017]

Parameter	With LHC 13 TeV and $(g-2)_\mu$	
	Best fit	'Nose' region
M_1	0.25 TeV	- 0.39 TeV
M_2	0.25 TeV	1.2 TeV
M_3	- 3.86 TeV	- 1.7 TeV
$m_{\tilde{q}}$	4.0 TeV	2.00 TeV
$m_{\tilde{q}_3}$	1.7 TeV	4.1 TeV
$m_{\tilde{\ell}}$	0.35 TeV	0.36 TeV
$m_{\tilde{\tau}}$	0.46 TeV	1.4 TeV
M_A	4.0 TeV	4.2 TeV
A	2.8 TeV	5.4 TeV
μ	1.33 TeV	- 5.7 TeV
$\tan\beta$	36	19
χ^2/d.o.f.	22.1/20	24.46/20
p-value	0.33	0.22
$\chi^2(HS)$	68.01	67.97

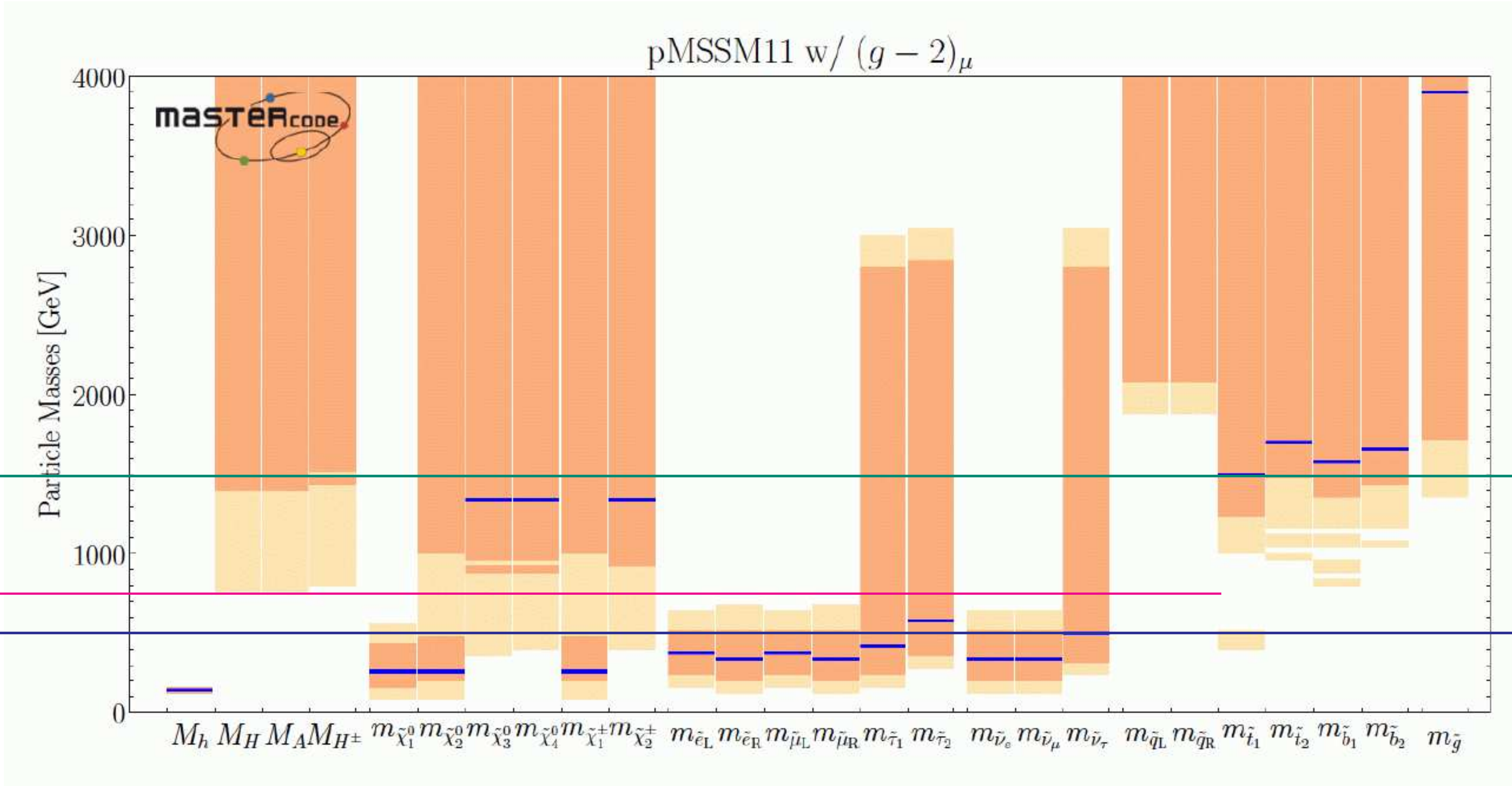
$\Rightarrow$ excellent p value!

pMSSM11: best-fit point phenomenology [2017]



⇒ heavy colored, light uncolored spectrum

pMSSM11: prospects for ILC and CLIC



ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of EW particle and DM easy!

ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ higher reach for non-diagonal production!

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ precision analysis of EW particles and DM easy!

What to conclude?

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$\Rightarrow$ **Look at the p values!**

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$\Rightarrow$ **Look at the p values!**

Model	Min. χ^2/dof	χ^2-prob. (p-value)
CMSSM	32.8/18	11%
NUHM1	31.1/23	12%
NUHM2	30.3/22	11%
SU(5)	32.4/23	9%
mAMSB	36.5/27	11%
pMSSM11	21.0/20	33%

Which model is more likely??

What to conclude?

$\Rightarrow$ **Look at the p values!**

Model	Min. χ^2/dof	χ^2-prob. (p-value)
CMSSM	32.8/18	11%
NUHM1	31.1/23	12%
NUHM2	30.3/22	11%
SU(5)	32.4/23	9%
mAMSB	36.5/27	11%
pMSSM11	21.0/20	33%

Which model is more likely??

$\Rightarrow$ pMSSM11: model with higher χ^2-probability
model with interesting ILC prospects
model with good CLIC prospects
detailed LHC analysis tbd!

4. $\phi_{96} \to \gamma\gamma$

– What was seen in Run I?

– What was seen in Run II?

– What was seen at LEP?

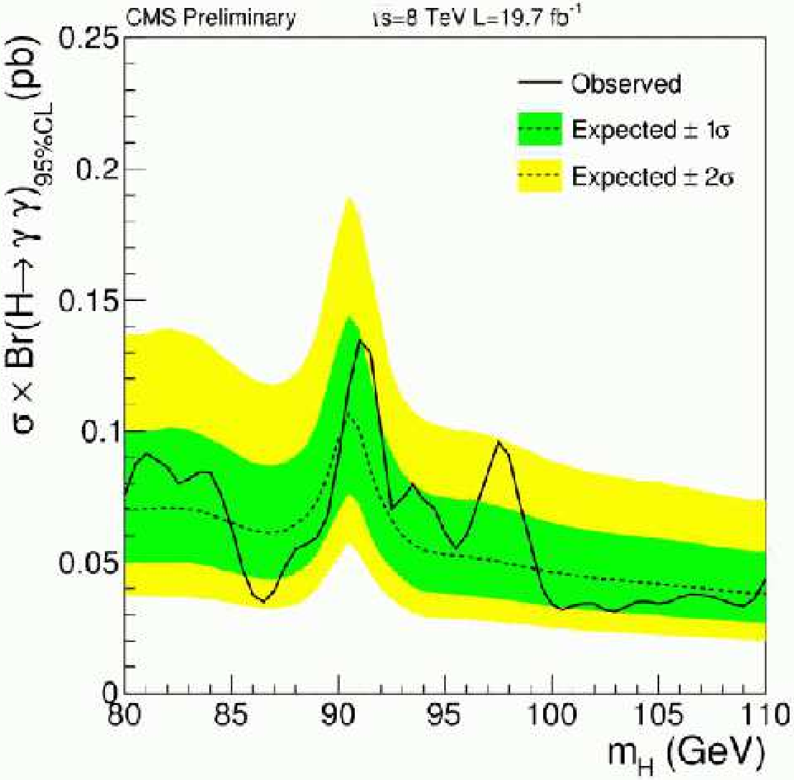
– Should we get excited?

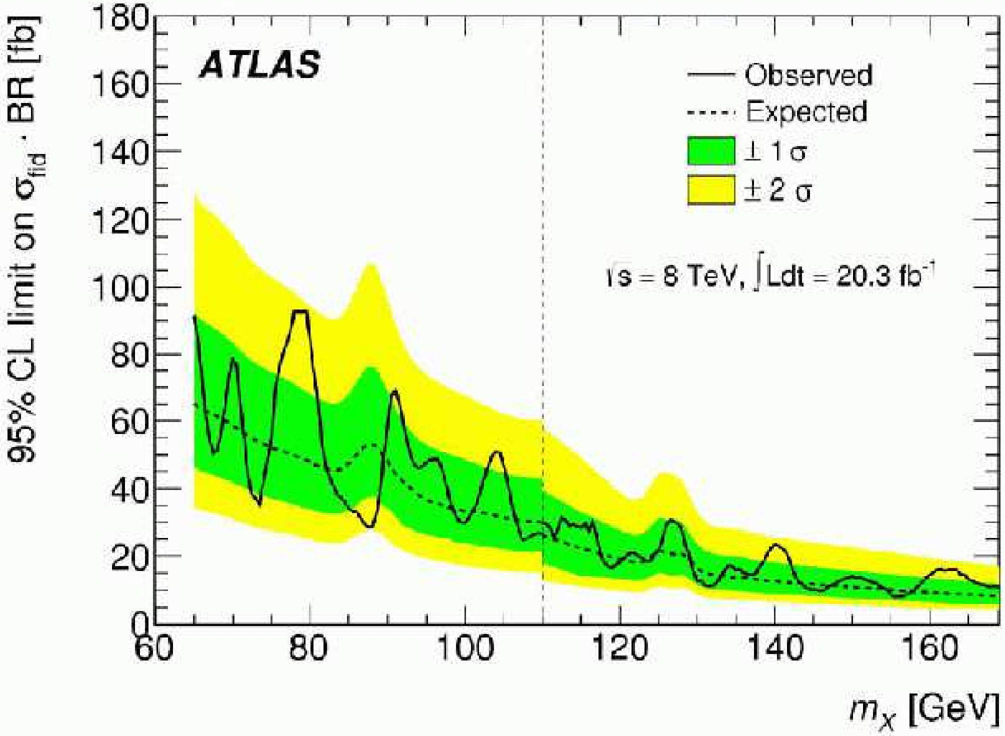
– Which model fits?

h-->γγ (65-110GeV) Run 1

CMS PAS HIG-14-037

PRL 113 171801 (2014)





- ~2σ excursion @~97.5 GeV
- ~2σ excursion @~80 GeV

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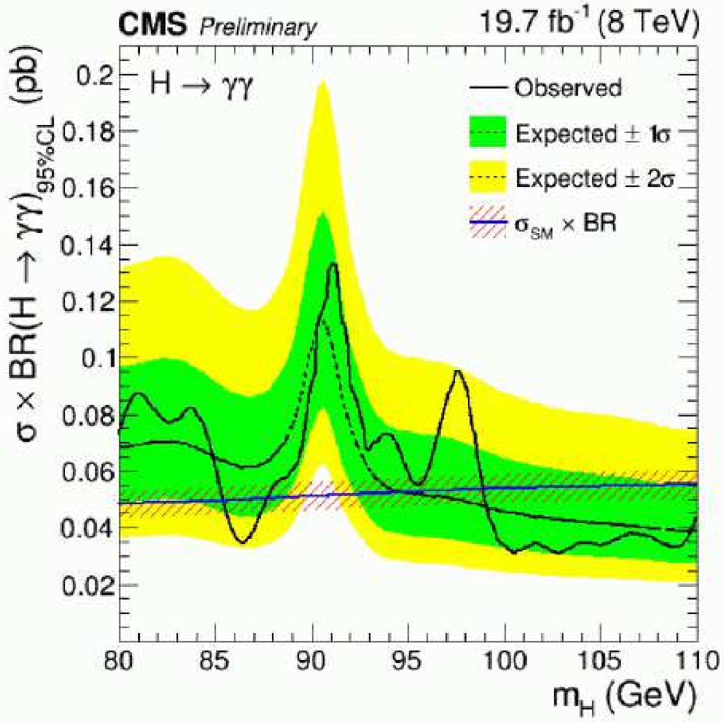
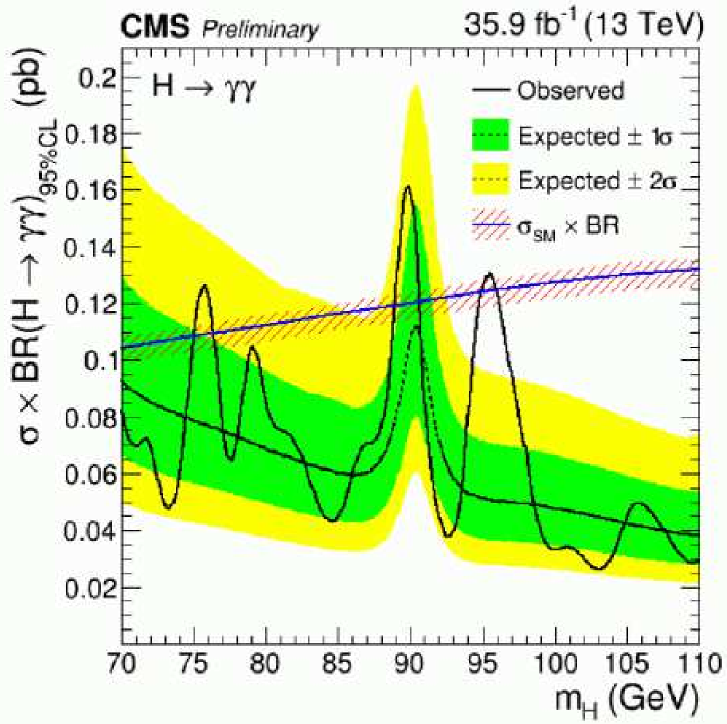
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

 [S. Shotkin, talk at HDays17]

h-->γγ (70-110 GeV) Runs 1+2

New!





CMS PAS HIG-17-013

8 TeV: minimum(maximum) limit on σ X Br : 31(133) fb at m=102.8(91.1)GeV

13 TeV: minimum(maximum) limit on σ X Br : 26(161) fb at m=103.0(89.9)GeV

- 8 TeV limits on σ X Br redone with 0.1 GeV step. Production processes assumed in SM proportions. No significant excess with respect to expected limits observed.

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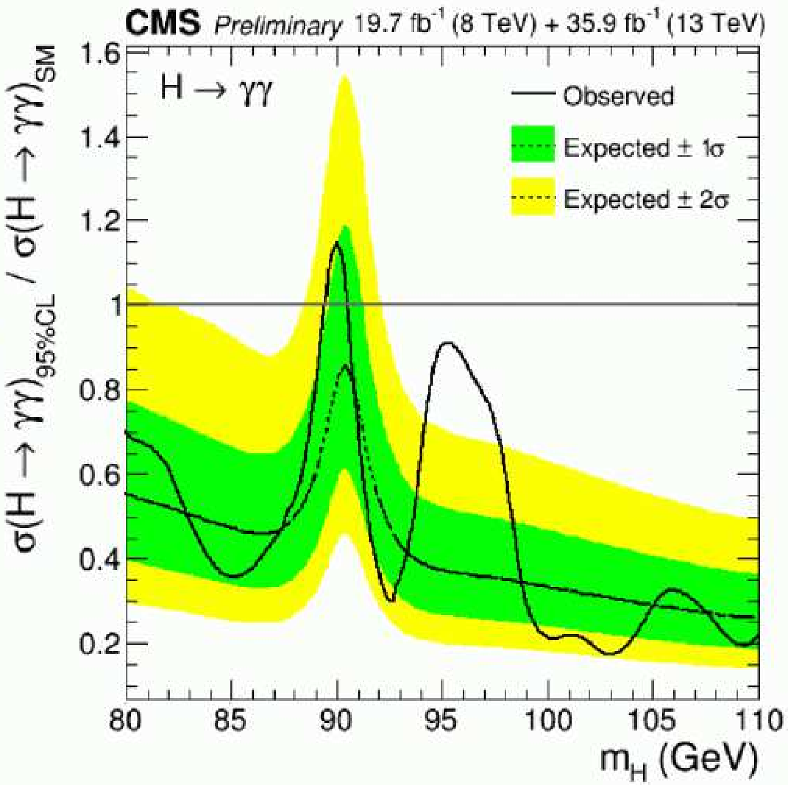
h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013

All experimental + theoretical systematic uncertainties assumed uncorrelated except for those on signal acceptance due to scale variations + those on production cross sections (assumed 100% correlated).



8 TeV+13 TeV: minimum(maximum) limit on $(\sigma \times Br)/(\sigma \times Br)_{SM}$: 0.17(1.15) at m=103.0(90.0)GeV

- Combined 8 TeV+13 TeV $\sigma \times$ BR limit normalized to SM expectation (production processes assumed in SM proportions). No significant excess with respect to expected limits observed.

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S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

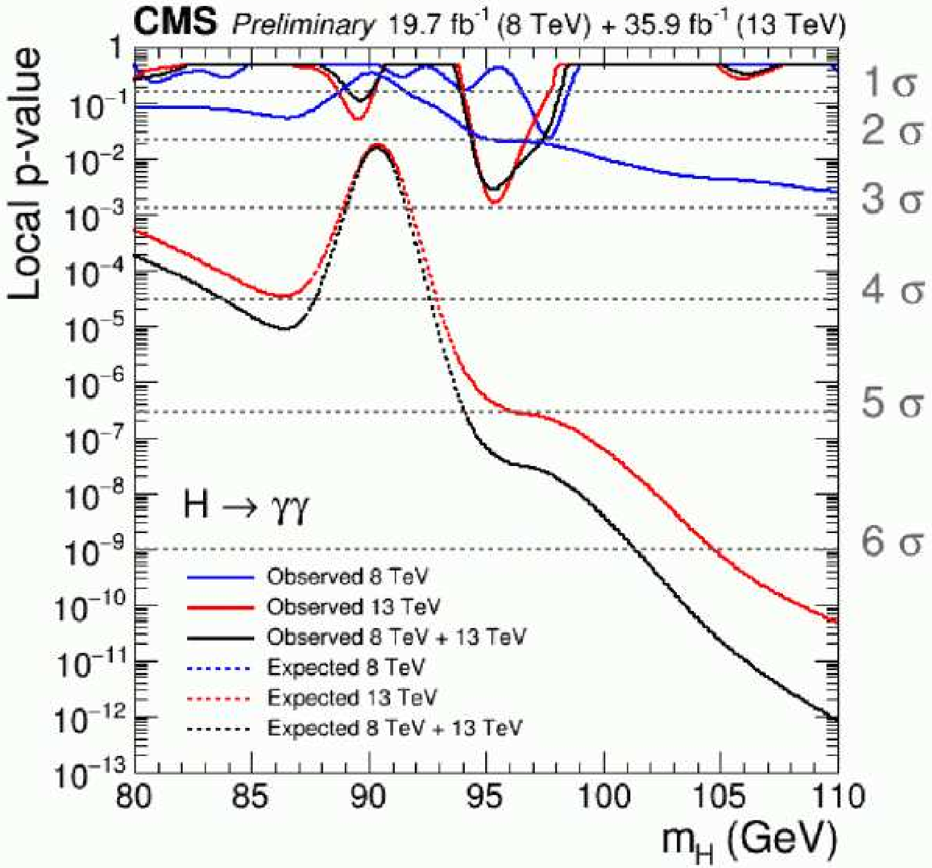
What was seen at Run II?

[S. Shotkin, talk at HDays17]

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013



8 TeV: Excess with ~2.0 σ local significance at m=97.6 GeV

13 TeV: Excess with ~2.9 σ local (1.47 σ global) significance at m=95.3 GeV

8TeV+13 TeV: Excess with ~2.8 σ local (1.3 σ global) significance at m=95.3 GeV

More data are required to ascertain the origin of this excess

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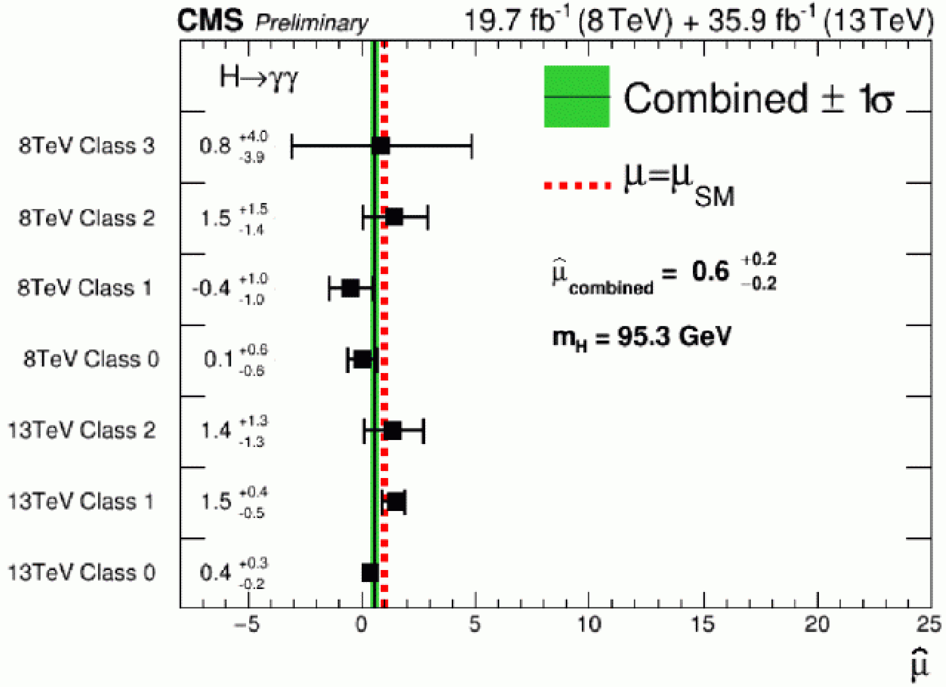
- Expected and observed local p-values for 8 TeV, 13 TeV and their combination

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

h-->γγ (70-110 GeV) Runs 1+2

New!

CMS PAS HIG-17-013



Excess here mostly driven by class 1 (&2) at 13 TeV

χ^2 probability for the seven individual values to be compatible with a single signal hypothesis: 41%

- 'Signal' strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing m_H=95.3 GeV
- More data are required to ascertain the origin of this excess

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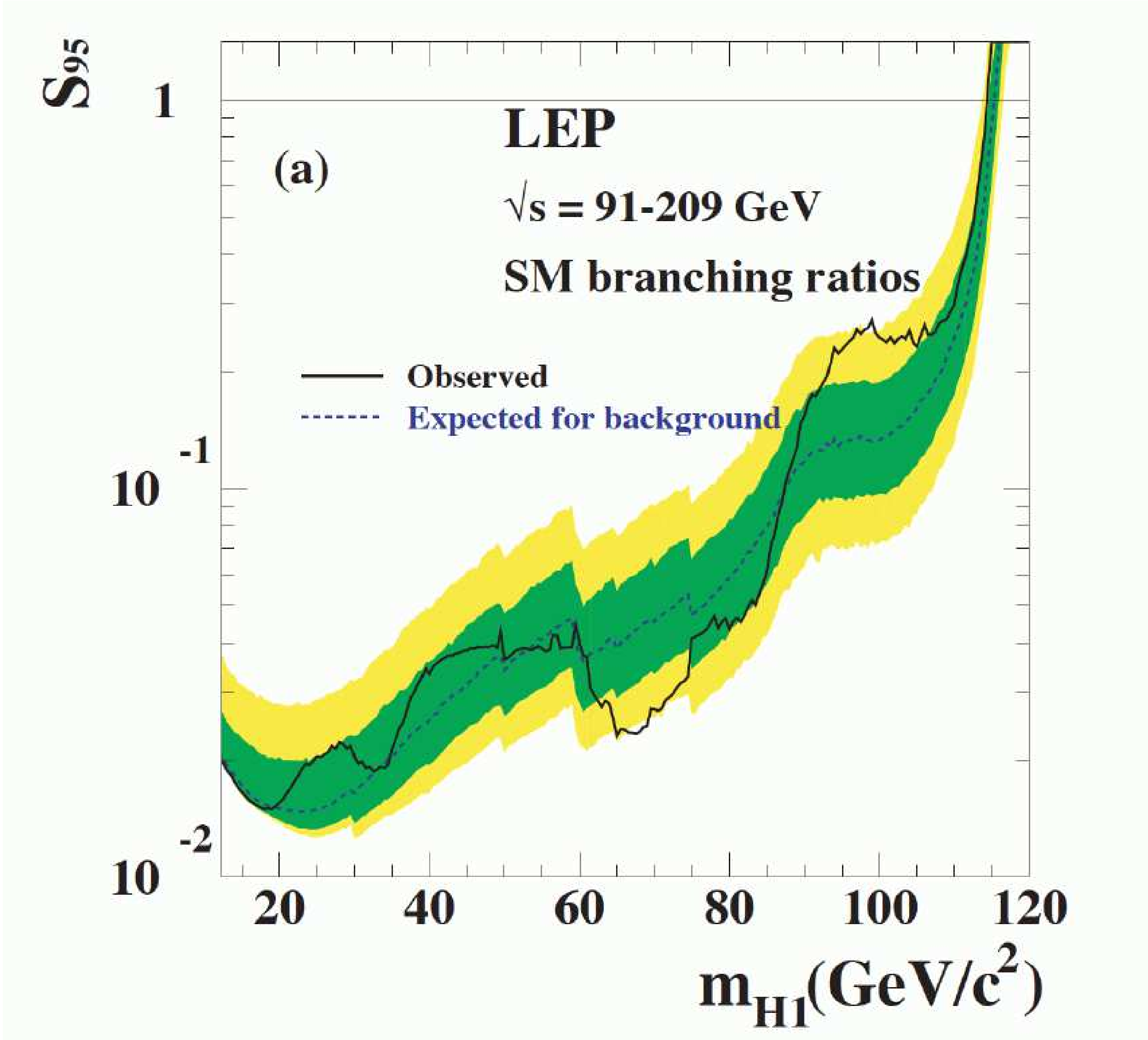
$$\mu_{\rm CMS}(96\ {\rm GeV}) = [\sigma(pp \to h_1) \times {\rm BR}(h_1 \to \gamma\gamma)]_{\rm exp/SM} = 0.6 \pm 0.2$$

What was seen at LEP?



$$\mu_{\text{LEP}}(98\text{ GeV}) = \left[\sigma(e^+e^- \to Zh_1) \times \text{BR}(h_1 \to b\bar{b})\right]_{\text{exp/SM}} = 0.117 \pm 0.057$$

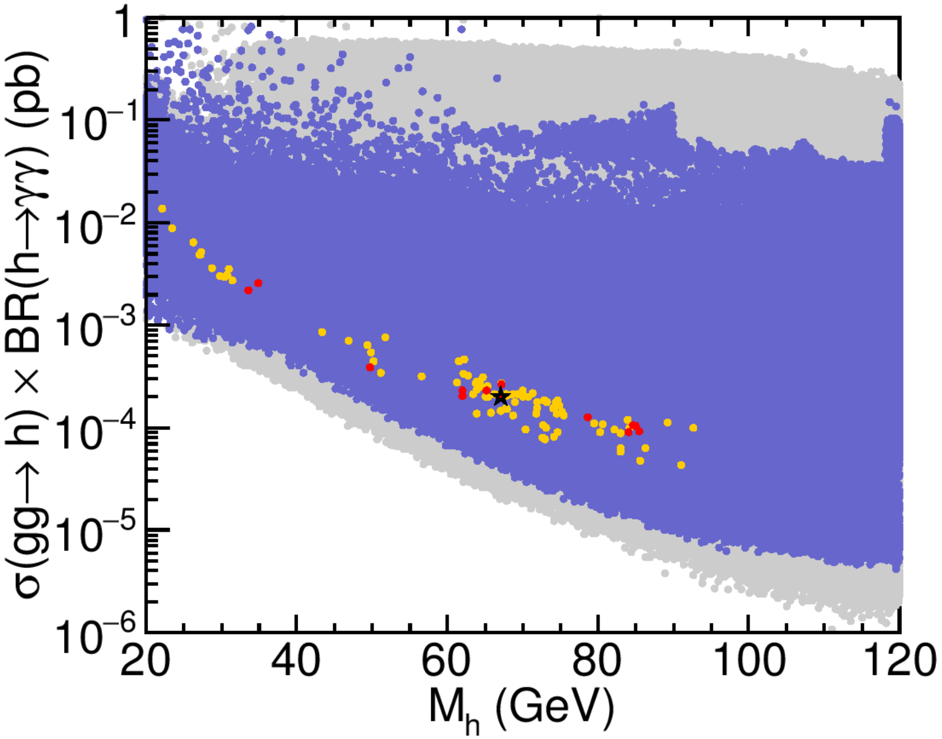
Should we get excited?

⇒ according to CMS no!

⇒ let's wait for ATLAS, ETA summer '18

Which model fits?

[*P. Bechtle, H. Haber, S.H., O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '16*]



⇒ not the MSSM

⇒ 2HDM? NMSSM?

Check the $\mu\nu$SSM

$\mu\nu$SSM: [*D. Lopez-Fogliani, C. Muñoz '06*]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)

$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

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$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

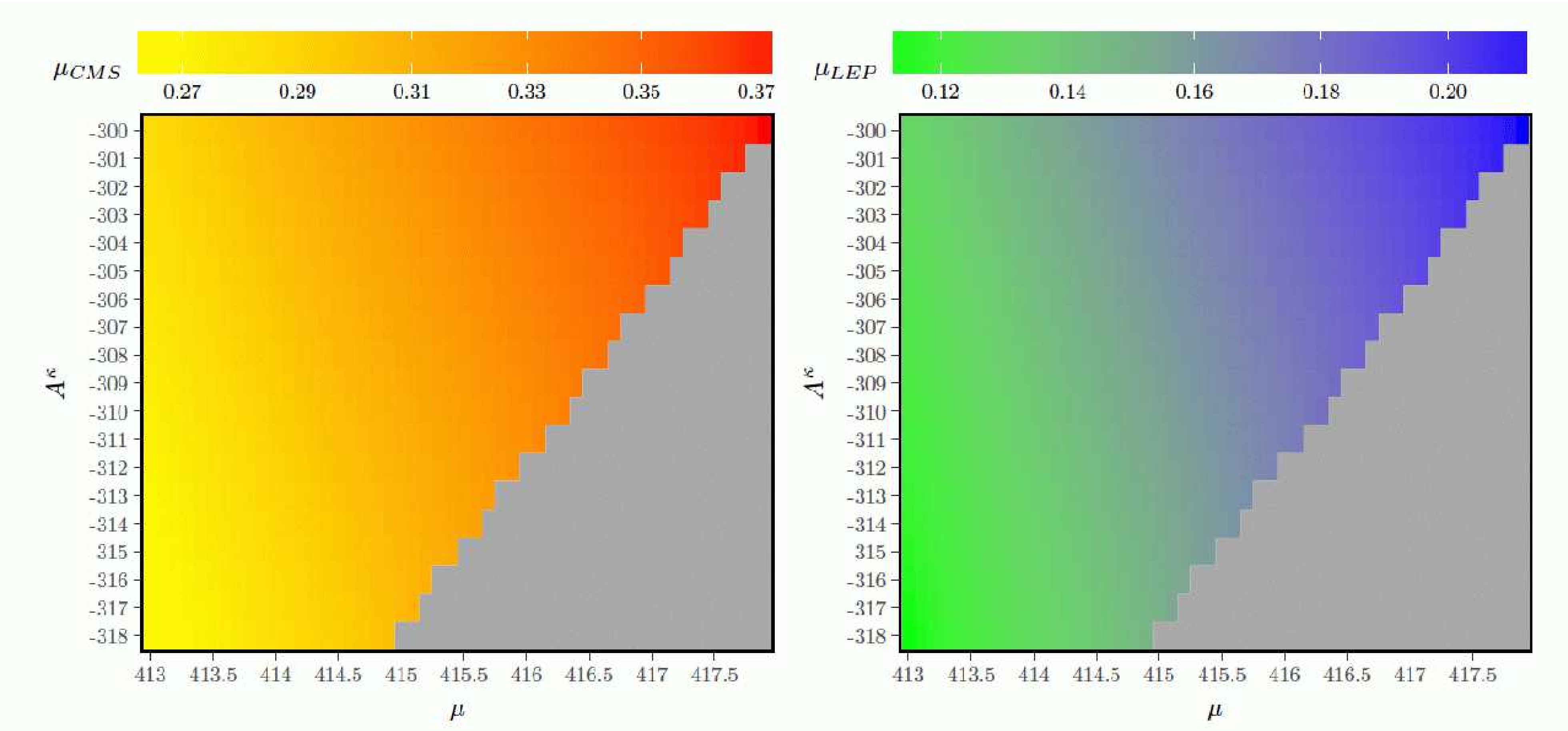
Can the $\mu\nu$SSM explain the two "excesses"?
[*T. Biekötter, S.H., C. Muñoz, arXiv:1712.07475*]

v_{iL}	Y_i^ν	A_i^ν	$\tan\beta$	μ	λ	A^λ	κ	A^κ	M_1
$\sqrt{2}\cdot 10^{-5}$	10^{-7}	-1000	2	$[413;418]$	0.6	956.035	0.035	$[-300;-318]$	100

M_2	M_3	$m^2_{\tilde{Q}_{iL}}$	$m^2_{\tilde{u}_{iR}}$	$m^2_{\tilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\tilde{e}})_{ii}$	A_{33}^e	$A_{11,22}^e$
200	1500	800^2	800^2	800^2	0	0	800^2	0	0

Can the $\mu\nu$SSM explain the two "excesses"?

[T. Biekötter, S.H., C. Muñoz, arXiv:1712.07475]



$\Rightarrow$ **YES, WE CAN! :-)**

(at the $1 - 1.5\,\sigma$ level)

5. Conclusinos

- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, SU(5), mAMSB
  - general models: pMSSM11, . . .
- MasterCode: LHC, Higgs, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation
-

Model	Min. χ^2/dof	χ^2-prob. (p-value)
GUT based models	$(30\ldots33)/(18\ldots23)$	$\sim 11\%$
pMSSM11	21.0/20	33%

$\Rightarrow$ pMSSM11: model with higher χ^2-probability
model with interesting (good) ILC (CLIC) prospects
detailed LHC analysis tbd!

- $\phi_{96} \to \gamma\gamma$: new CMS result possibly interesting!
  $\mu\nu$SSM can explain CMS and LEP "excesses"


Further Questions?